Secondary eyewalls:
Lessons learned and their presence in operational HWRF

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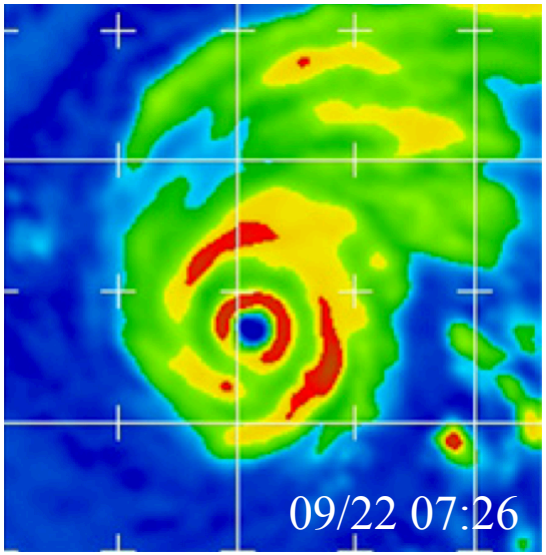
Acknowledge the whole HWRF team

[1] EMC
[2] FSU

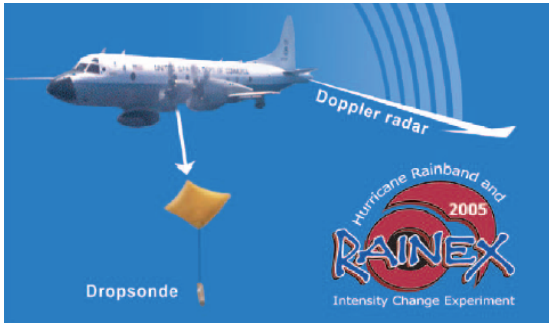
Outline

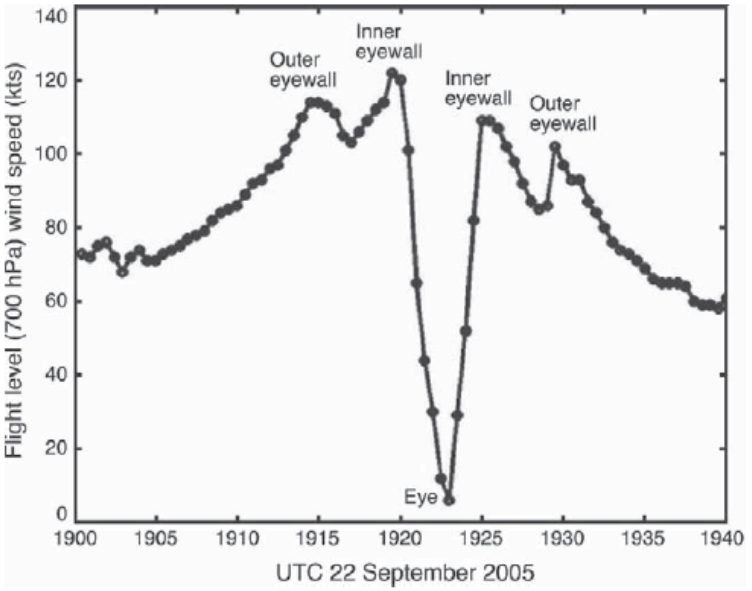
- **Introduction**
  - What constitutes a secondary eyewall (SEs)?
  - Frequency: Nature Vs mesoscale integrations
- **Relevant scientific lessons**
  - Intensification
    - Mean flow & eddies
    - Balance & Unbalanced dynamics
  - SEF a progressive (!) process
- **SEs in HWRF**
  - Edouard (2014), NASA HS3

Rita (2005)



Brightness temperature, from Aqua/AMSR-E (at 89 GHz)





Houze et al. (2006)

Secondary eyewall:
A structure approximately concentric to the primary eyewall characterized by a maxima in:

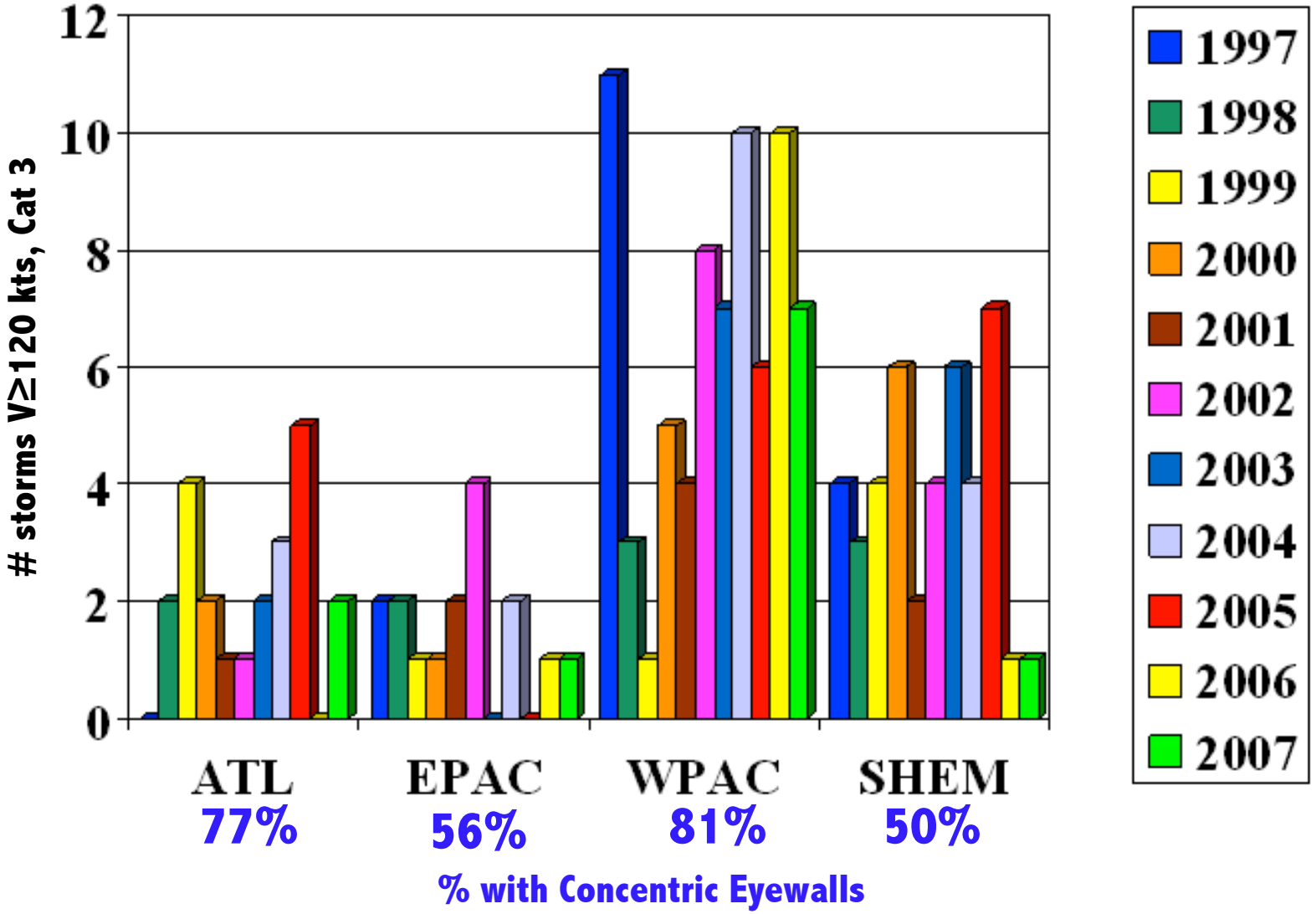
a) Convective activity
b) Tangential winds

Secondary eyewall formation

Maxima in:

- **Tangential wind tendency**
- **Radial convergence**

SEs are a common feature of intense storms

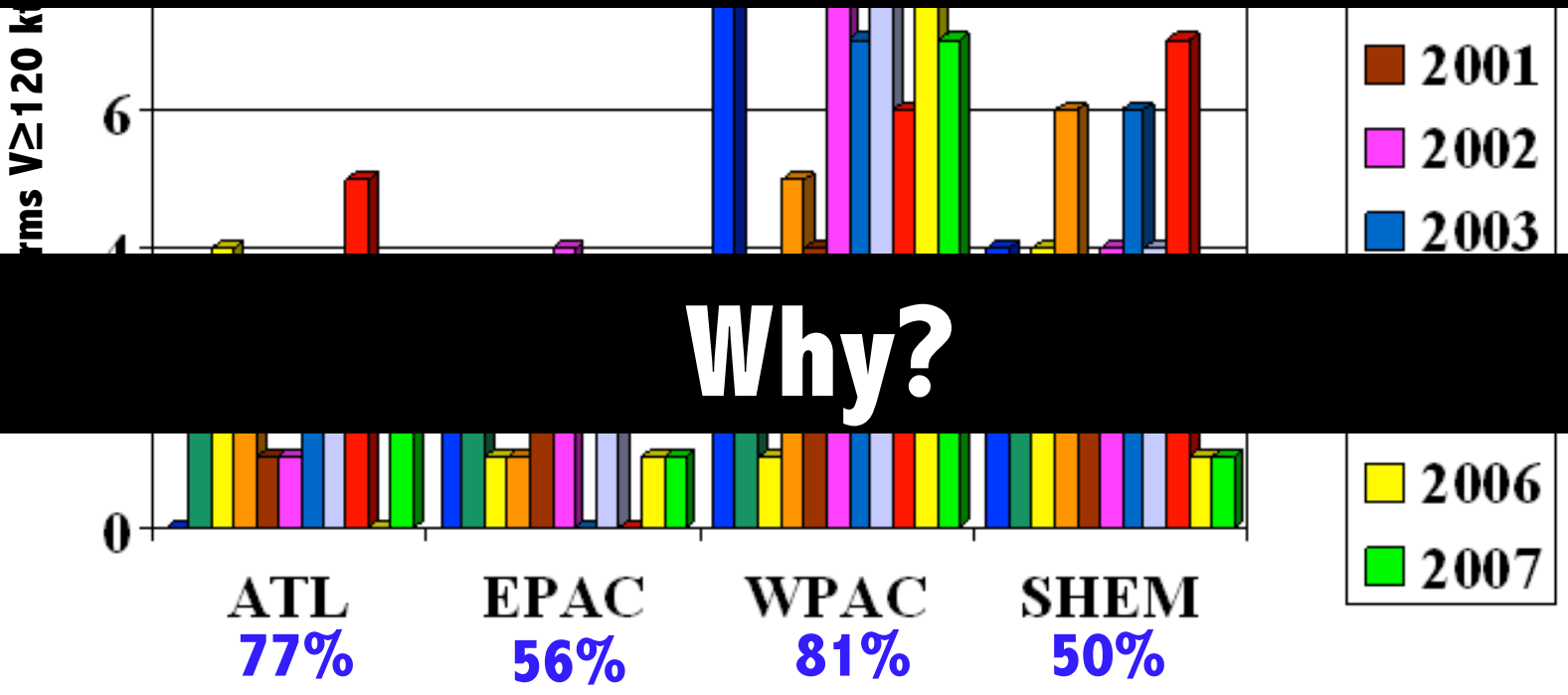


Hawkins and Helveston (2008)

SEs are a common feature of intense storms

Not in mesoscale simulations!

~6% in AHW



Why?

Hawkins and Helveston (2008)

Table 2-1: Names of AHW simulations screened for secondary eyewalls.

Year	Name	Maximum Saffir-Simpson category	Observed SE in nature	Number of simulations screened
2005	Emily	4		2
2005	Katrina	5	√	7
2005	Rita	5	√	7
2005	Wilma	5	√	3
2007	Dean	5	√	3
2007	Felix	5	√	7
2008	Ike	4	√	8
2009	Bill	4	√	12
2009	Fred	3		7
2009	Gustav	4	√	4
2010	Igor	4	√	3
			Total:	60

SEs are rare in AHW

Table 2-2: AHW simulations with secondary eyewalls analyzed in subsequent chapters.

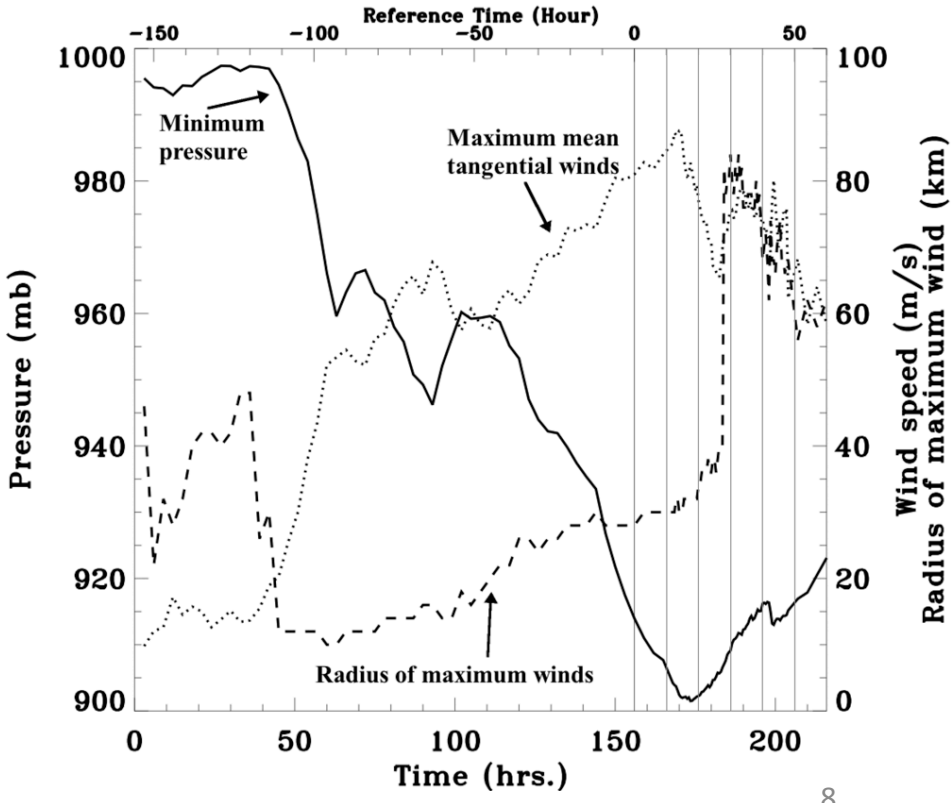
Storm		AHW version	Microphysical scheme	Initialization [day/month]	Initialization [UTC]	Output frequency [min]
Katrina 2005	K60	2.2	WSM5	27/08	00	60
Rita 2005	R60	2.2	WSM5	21/09	00	60
Katrina 2005	K10	2.1.2	WSM3	27/08	00	10
Igor 2010	R10	3.2	Thompson	11/09	00	10

Abarca (2011)

Idealized RAMS simulation

SEF only at hr~180

- Walko et al. (1995) microphysics (7 species)
- Louis (1979) scheme, surface fluxes
- Three domains, 24, 6, 2 km
- f-plane at 15°N
- SST 28°C
- Initial environment at rest
  - Weak mesoscale vortex
  - Gradient and hydrostatic balance
  - V_{max}=10 m s^{-1} RMW at 75 km
  - Warm bubble, moisture perturbation

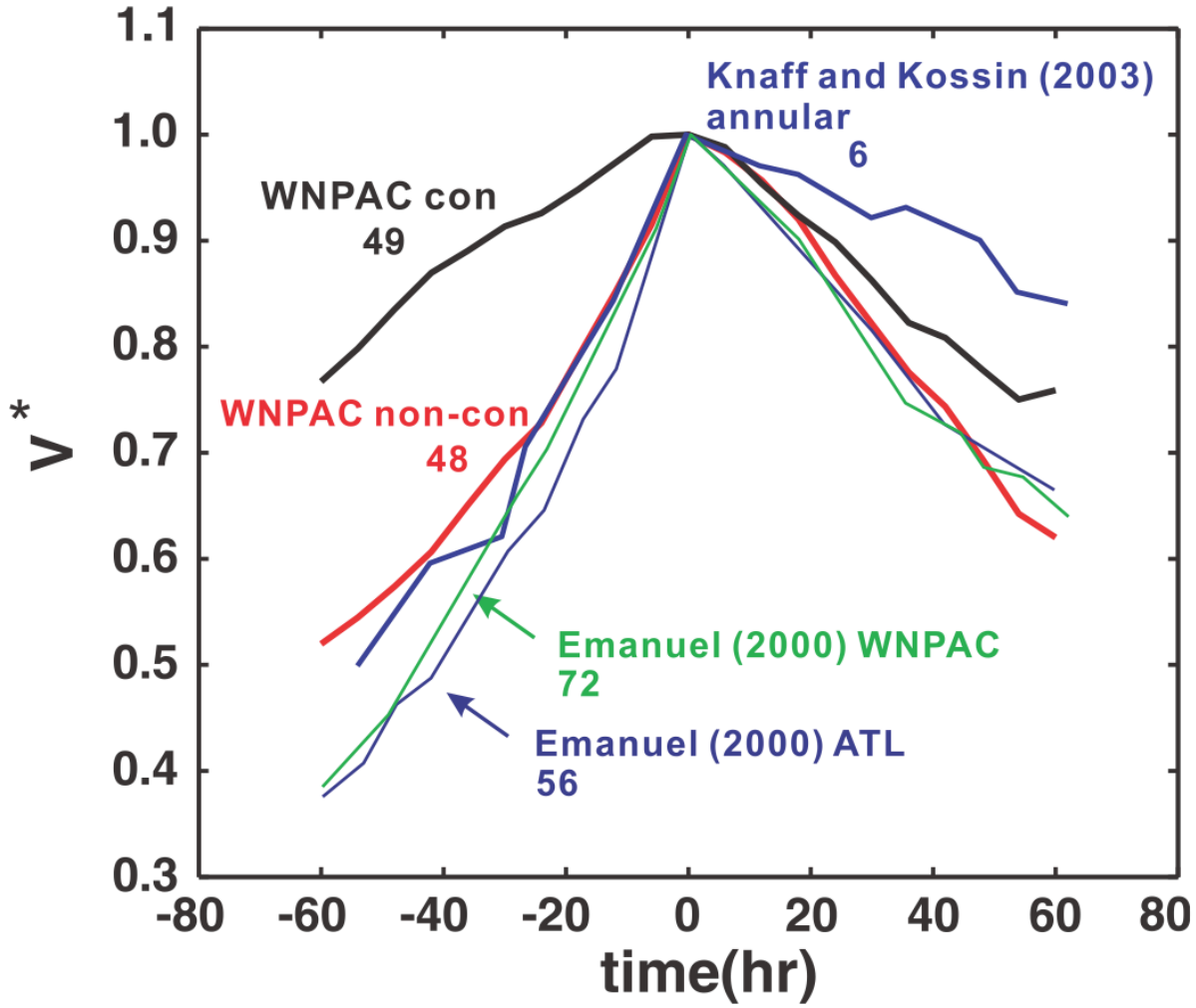


Terwey & Montgomery (2008)

Terwey, Abarca & Montgomery (2013)
Abarca & Montgomery (2013)
Montgomery, Abarca, Smith, Wu & Huang (2013)
Abarca & Montgomery 2014a; 2014b)

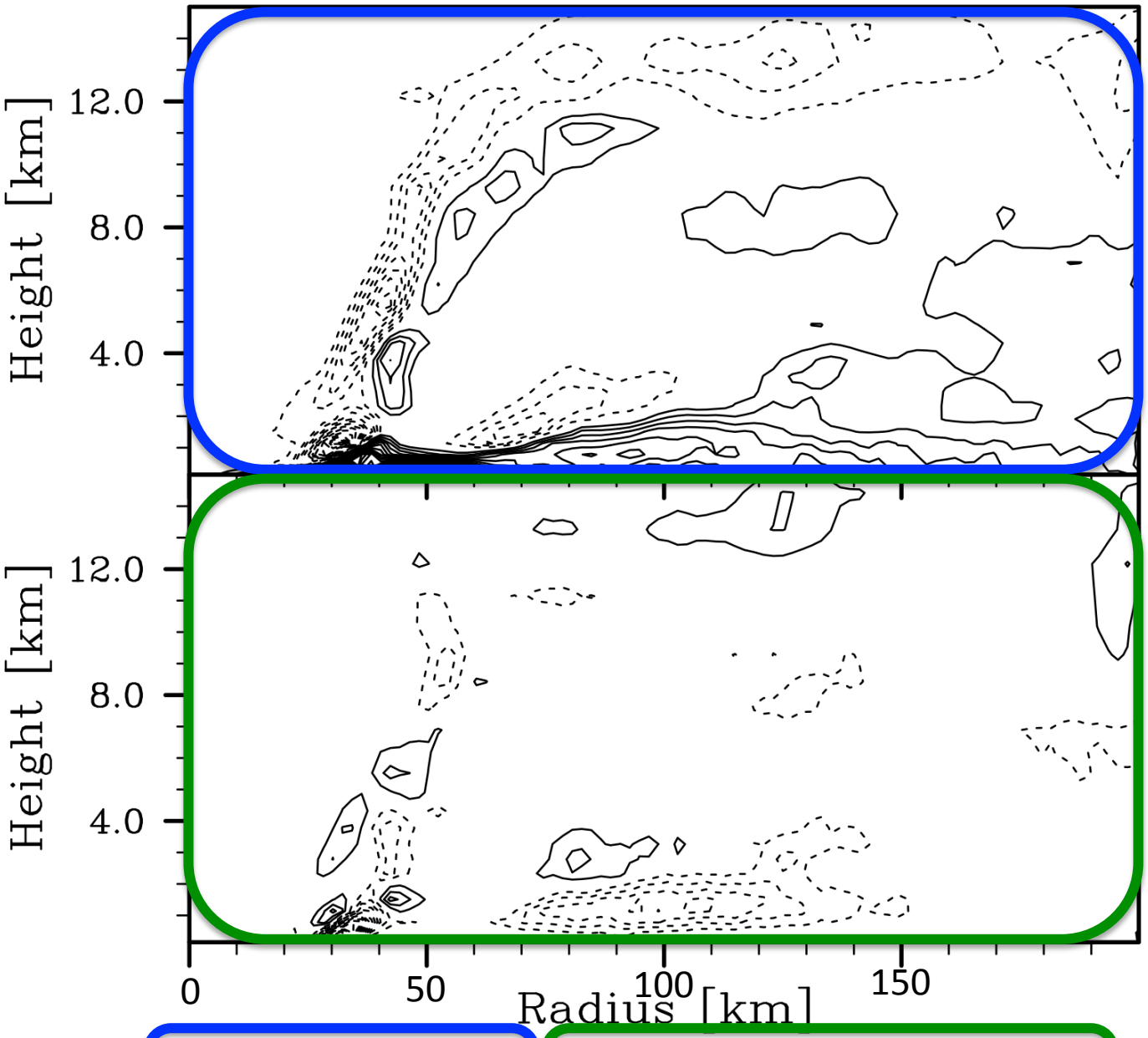
225 Typhoons (1997-2006)

Landfall cases excluded



Concentric eyewalls: Longer duration of higher storm intensity

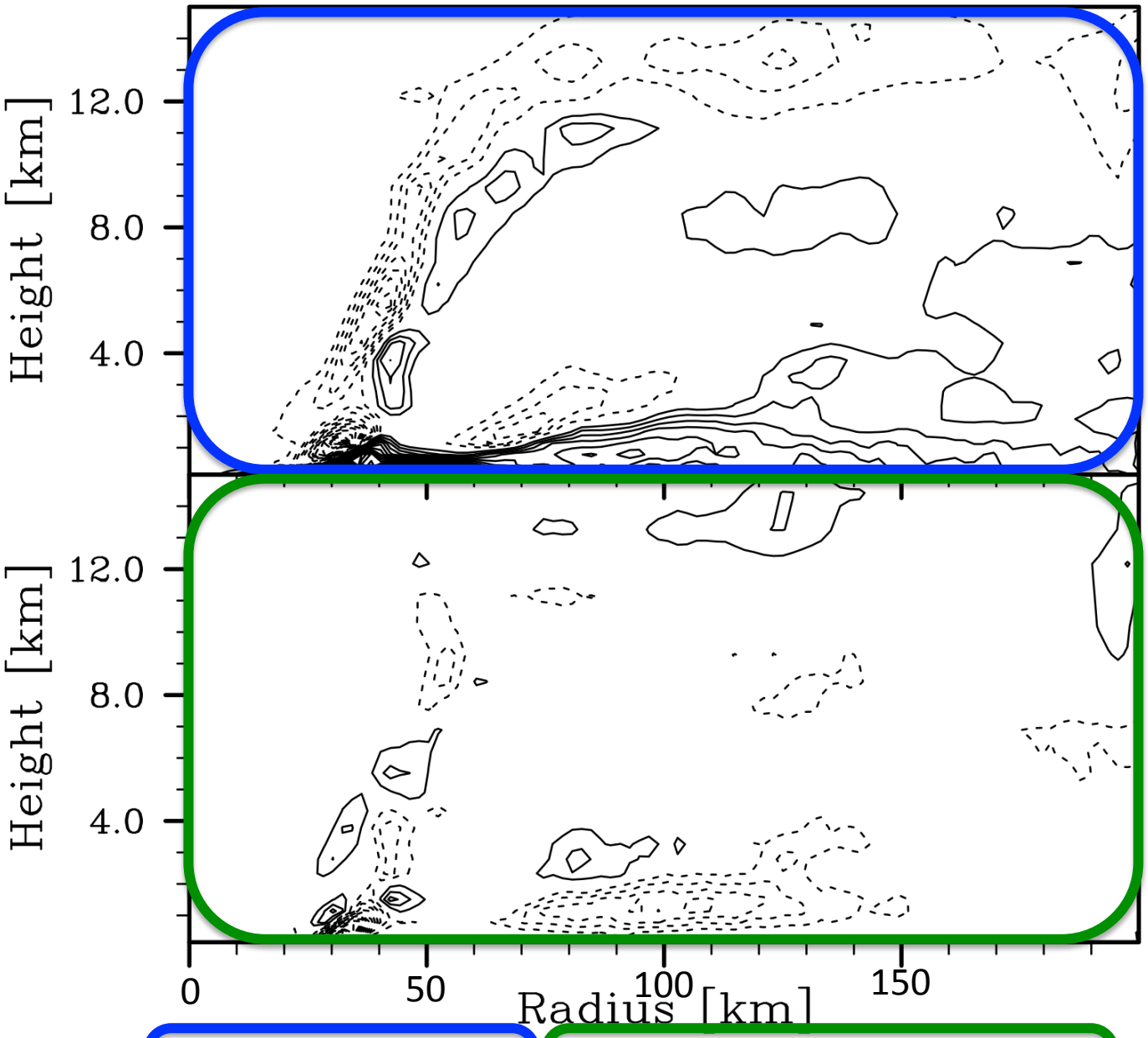
Kuo et al. (2009)



Mean Dynamics

- **Balanced?**
- **Linear?**

$$\frac{\partial \langle v \rangle}{\partial t} = -\langle u \rangle \langle \zeta_a \rangle - \langle w \rangle \frac{\partial \langle v \rangle}{\partial z} - \langle u' \zeta'_a \rangle - \left\langle w' \frac{\partial v'}{\partial z} \right\rangle - \left\langle \frac{1}{\rho} \frac{\partial p'}{\partial \lambda} \right\rangle + \langle F \rangle$$



Mean Dynamics

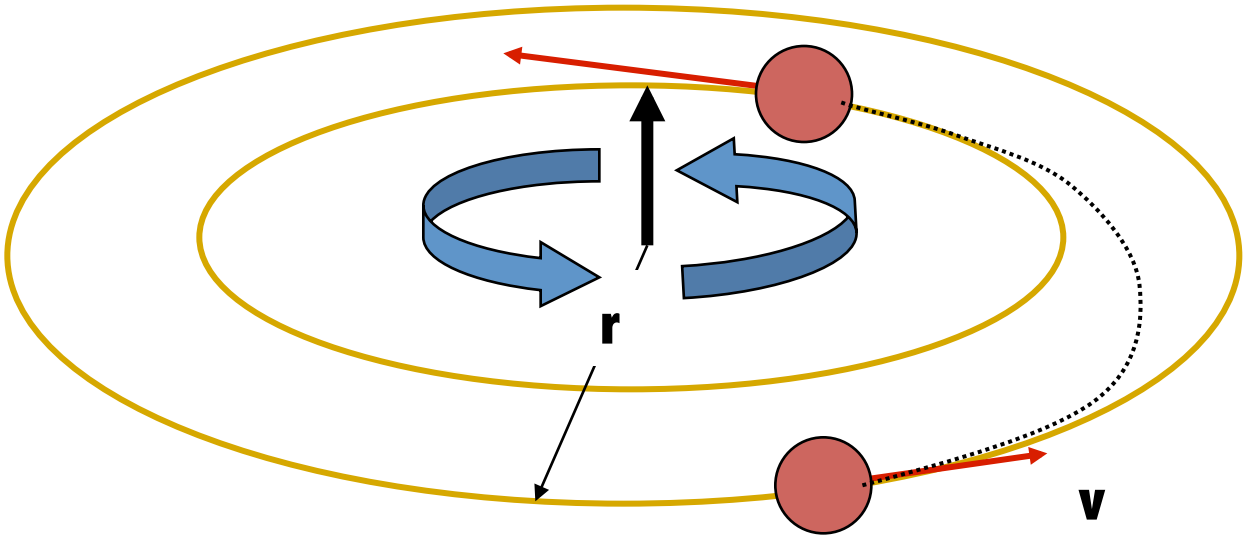
- Balanced?
- Linear?

Very MEAN dynamics

$$\frac{\partial \langle v \rangle}{\partial t} = -\langle u \rangle \langle \zeta_a \rangle - \langle w \rangle \frac{\partial \langle v \rangle}{\partial z} - \langle u' \zeta'_a \rangle - \left\langle w' \frac{\partial v'}{\partial z} \right\rangle - \left\langle \frac{1}{\rho} \frac{\partial p'}{\partial \lambda} \right\rangle + \langle F \rangle$$

Basic principle of hurricane intensification

$$M = rv + r^2 f/2$$



$$v = M/r - rf/2$$ ⇒ **As r decreases, v increases**

What causes radial convergence of M?

Montgomery and Smith (2013)

Radial convergence of M:

1st Mechanism

- Above the BL (M~conserved)
  - •Radial gradient of diabatic heating
    - •Convective structures
    - •Presence of surface moisture fluxes
    - •Described in terms of ***balanced dynamics***

2nd Mechanism

- •Within the BL (M~ not conserved)
  - •Friction is important
  - •In a coupled system of equations!
  - •Presence of supergradient winds

$$\frac{Du}{Dt} = \underbrace{-\frac{1}{\rho}\frac{\partial p}{\partial r} + \frac{v^2}{r} + fv}_{=0} + F_r$$

$$\frac{\partial v}{\partial t} = -u\zeta_a - w\frac{\partial v}{\partial z} + F_\lambda$$

$$\frac{Dw}{Dt} = \underbrace{-\frac{1}{\rho}\frac{\partial p}{\partial z} - g}_{=0} + F_z$$

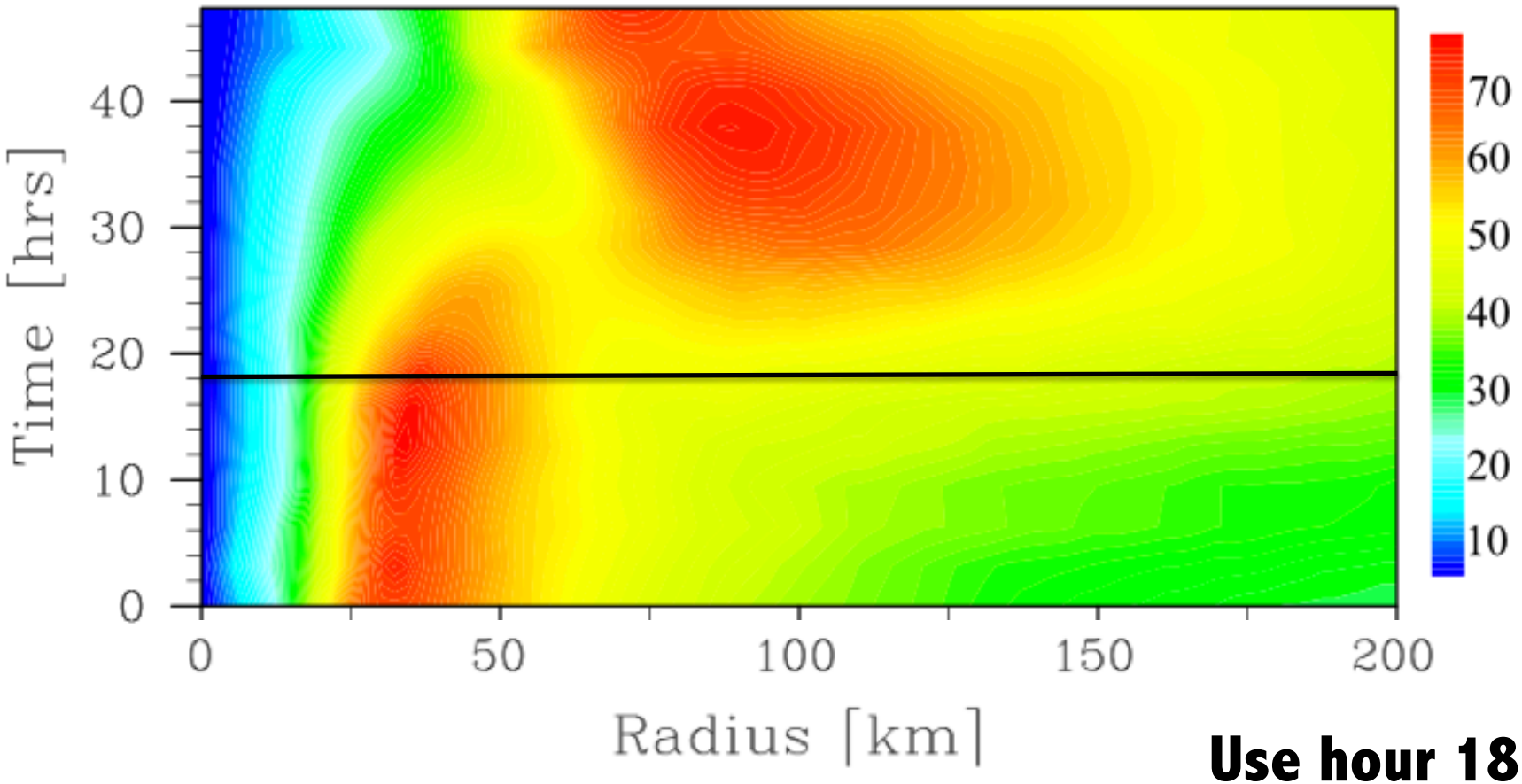
Thermal wind equation

Vortex

- **Subject to diabatic/frictional forcing**
- **Develop a secondary circulation to remain in balance**

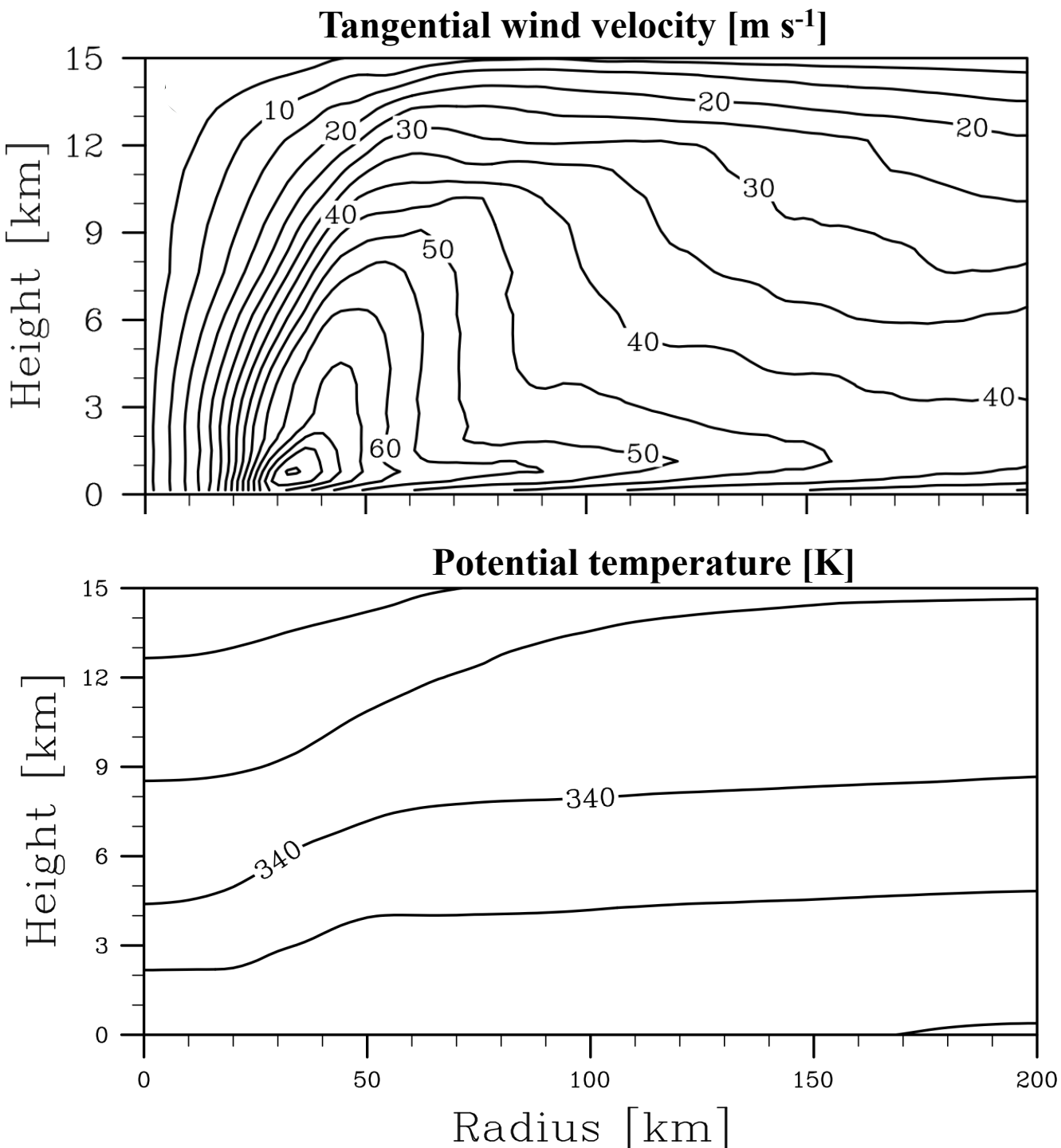
z=1,512m

Tangential wind velocity [m s^{-1}]



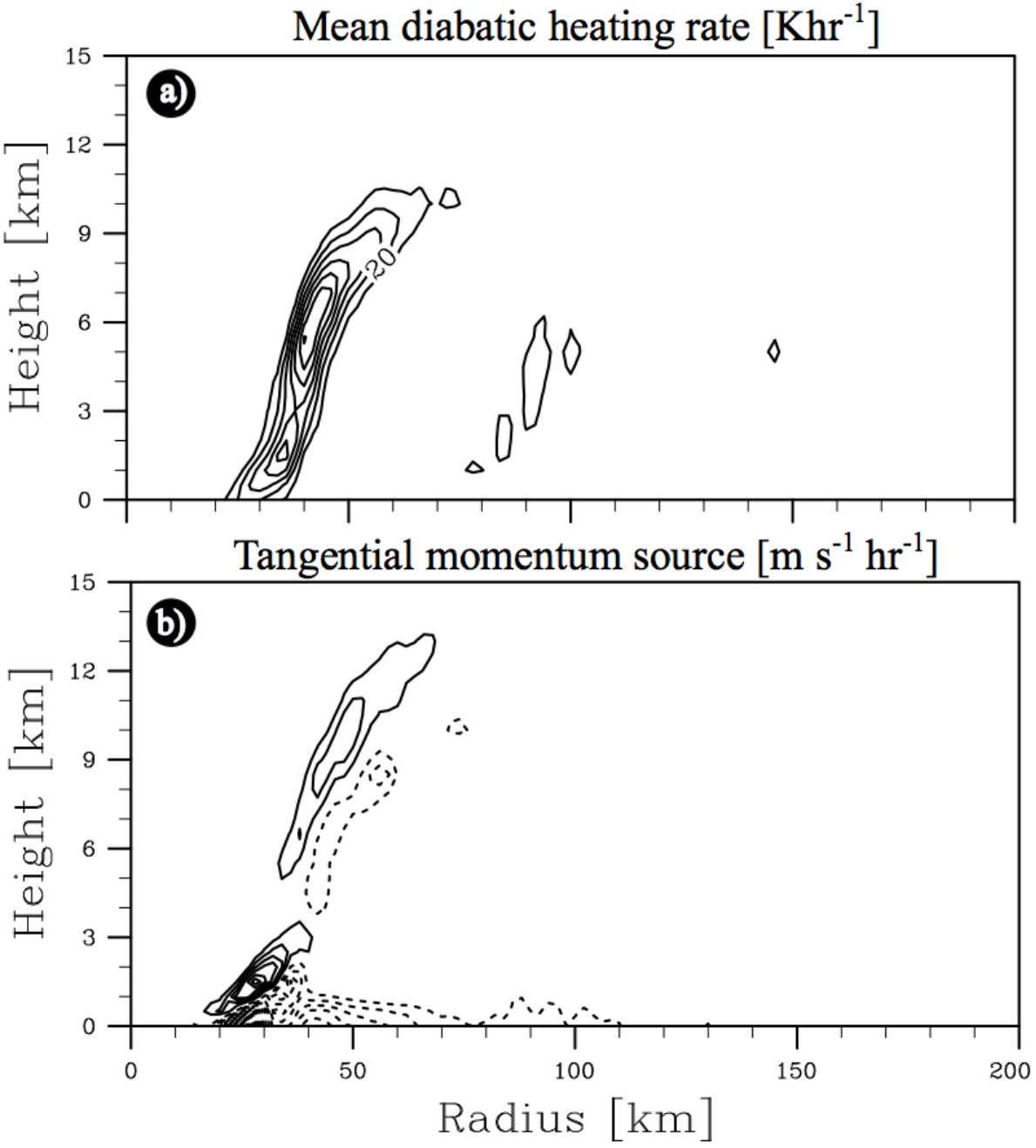
Use hour 18

Abarca and Montgomery (2013)


Tangential wind velocity [m s-1]
Height [km]
15
12
9
6
3
0
10
20
30
40
50
60
20
20
30
40
40
50
Potential temperature [K]
Height [km]
15
12
9
6
3
0
340
340
0
50
100
150
200
Radius [km]

$$Q = \bar{\dot{\theta}} - \overline{u'\frac{\partial \theta'}{\partial r}} - \overline{\frac{v'}{r}\frac{\partial \theta'}{\partial \lambda}} - \overline{w'\frac{\partial \theta'}{\partial z}}$$

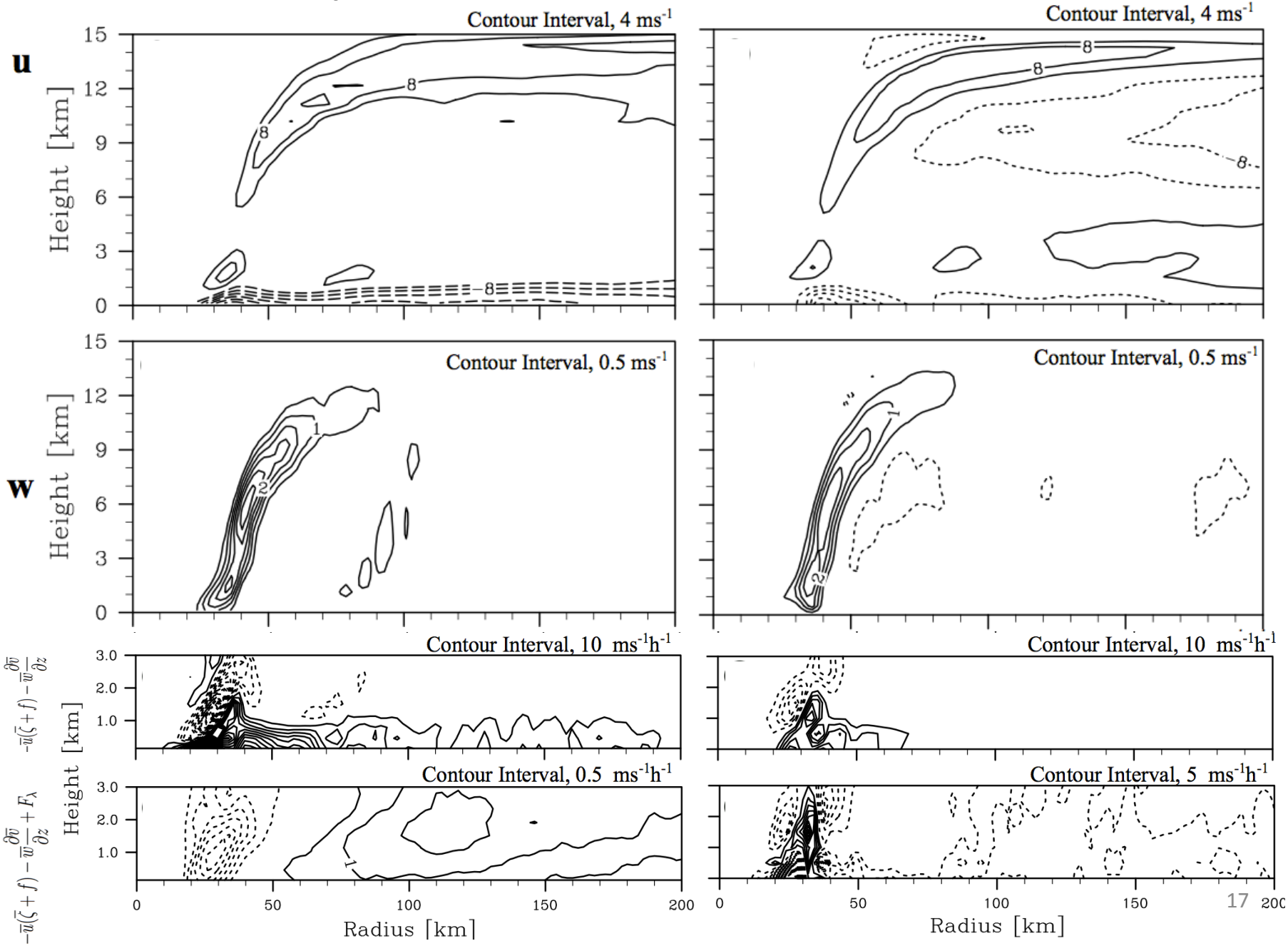
$$F_\lambda = \frac{\partial \bar{v}}{\partial t} + \bar{u}\zeta_a + \bar{w}\frac{\partial \bar{v}}{\partial z}$$



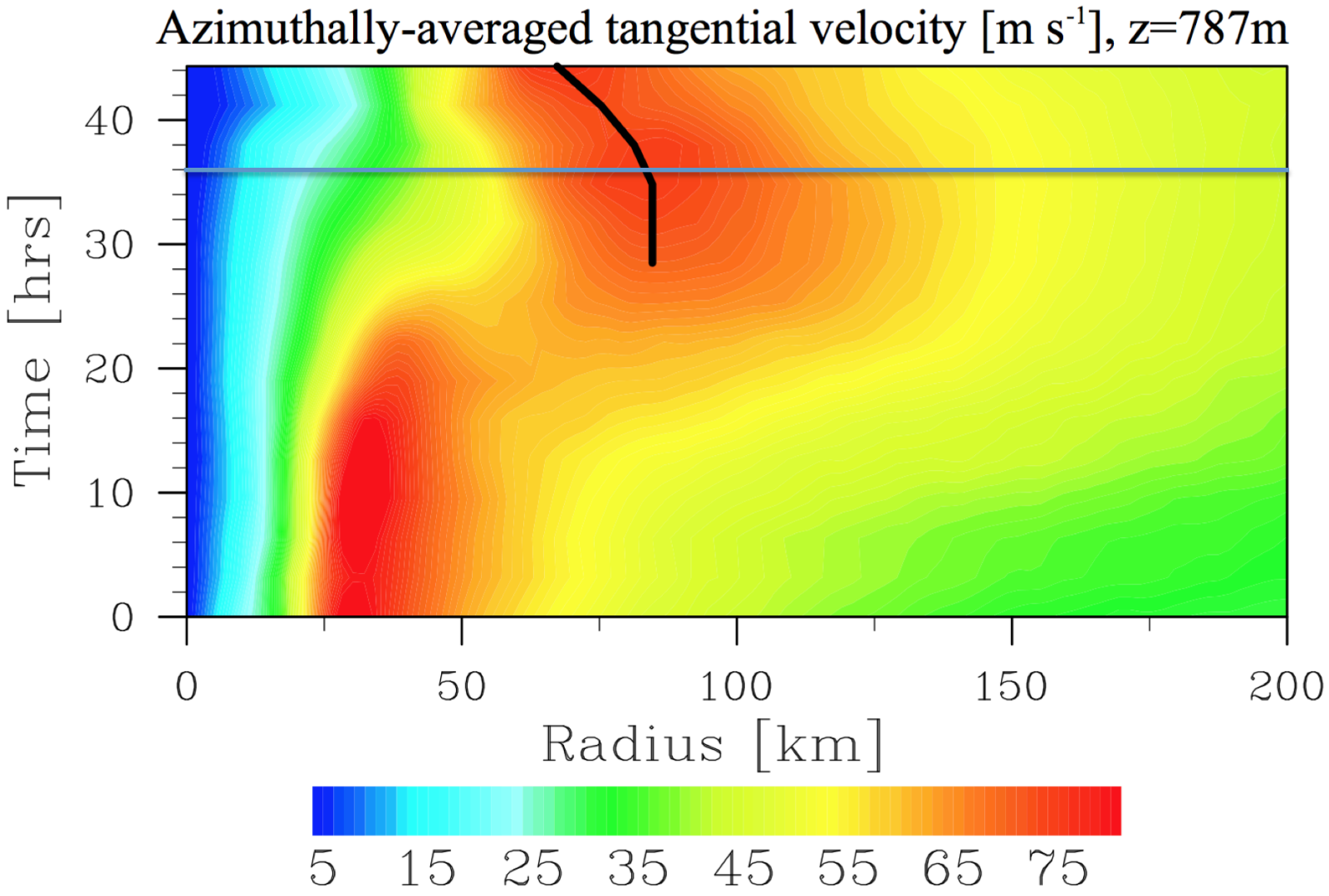
Abarca and Montgomery (2013b)

Full physics model

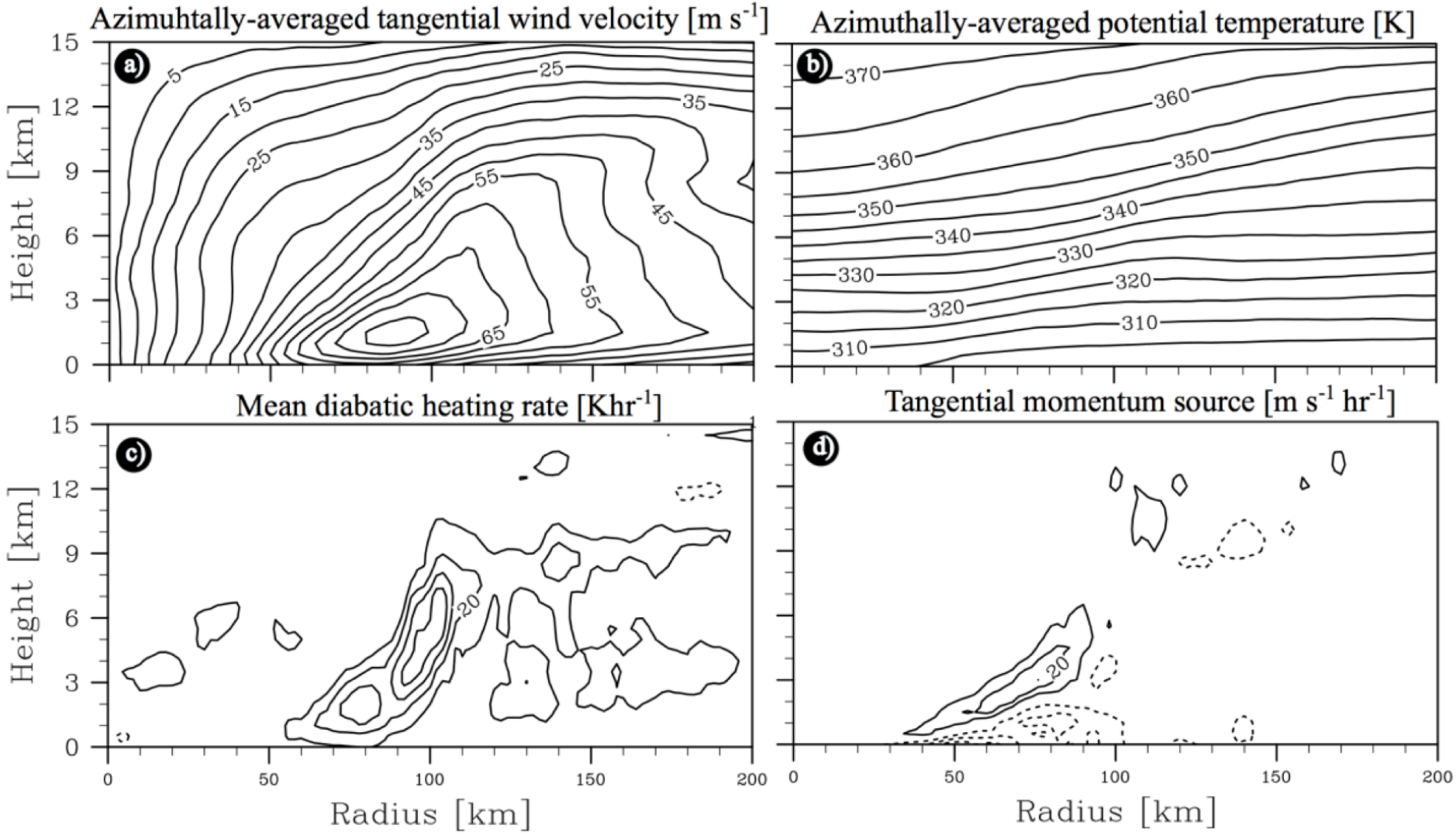
Balanced



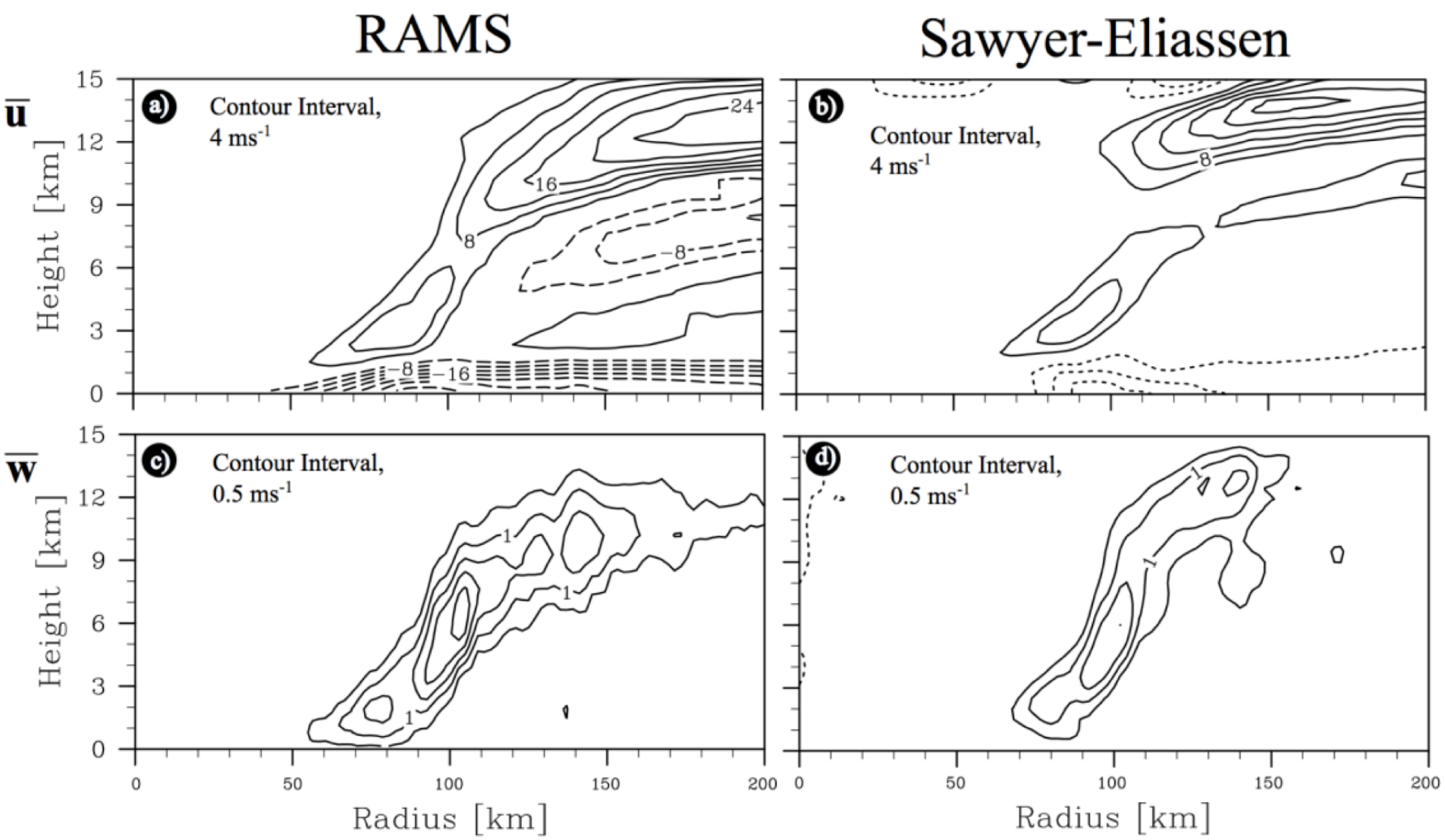
SEF… now how about ERC?



Abarca and Montgomery (2014b)

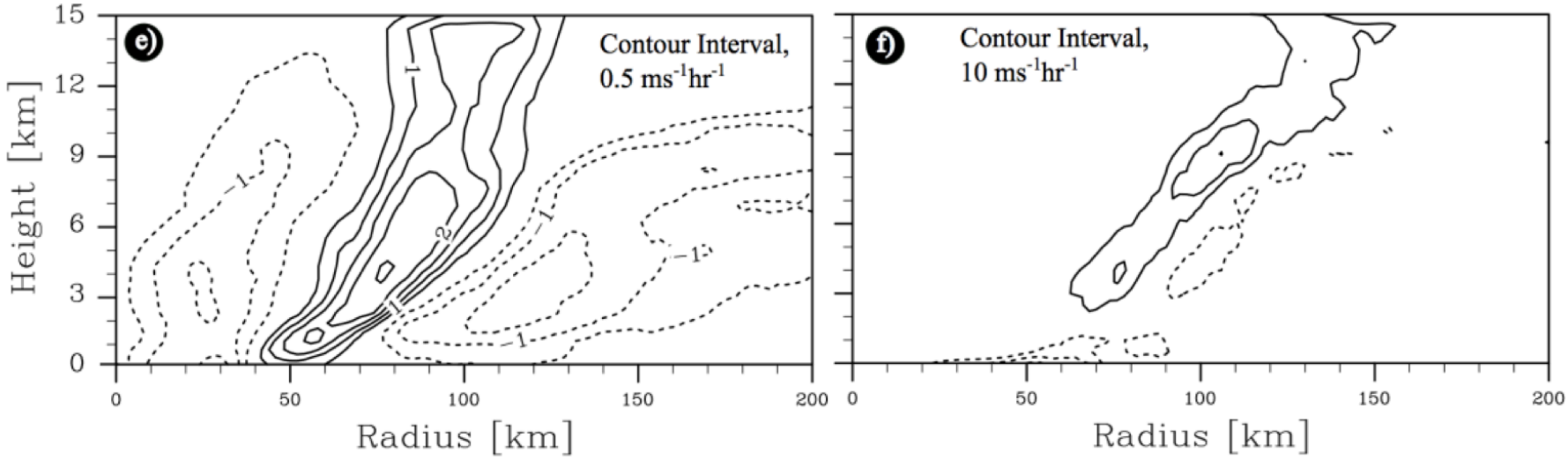


Abarca and Montgomery (2014b)

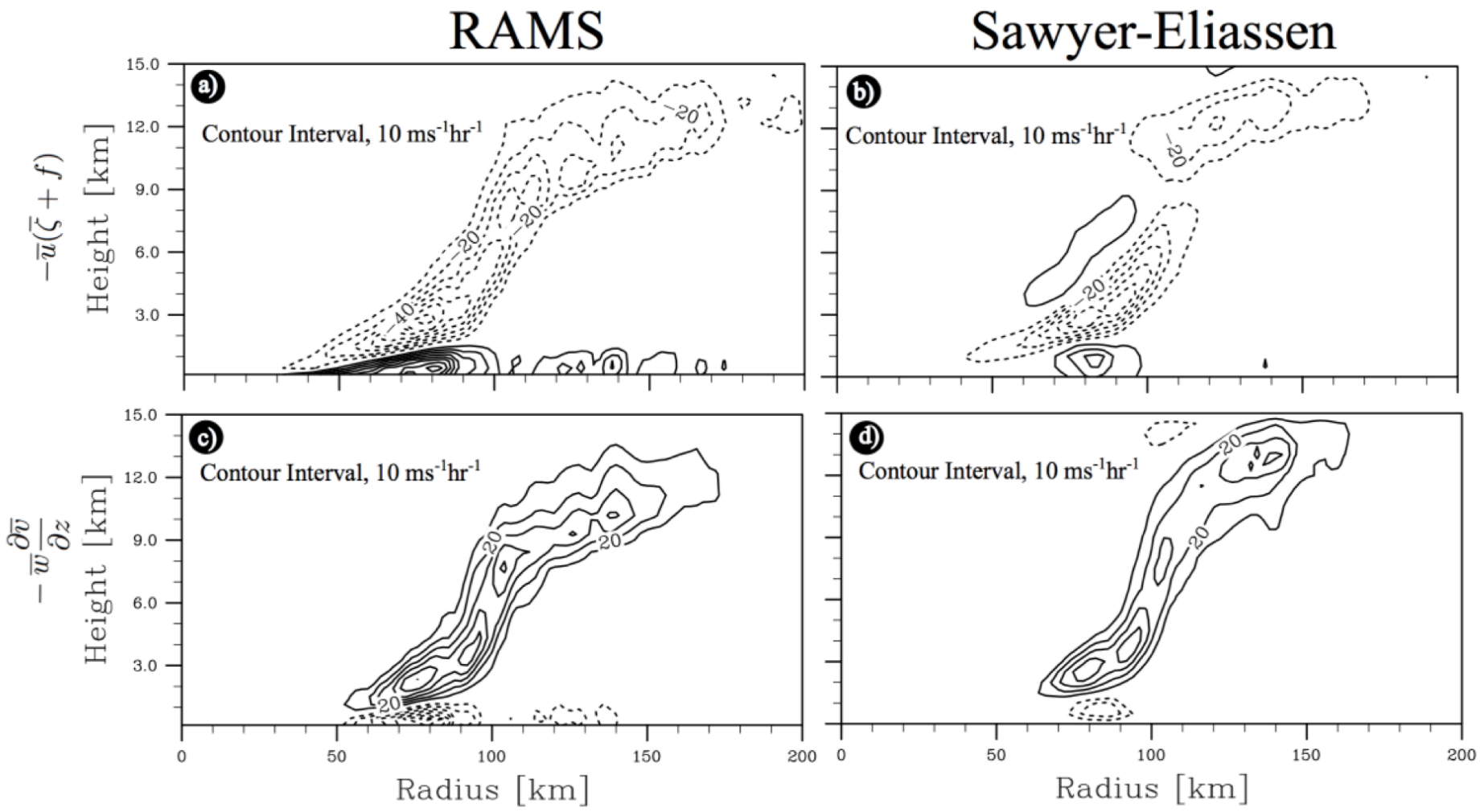


Abarca and Montgomery (2014b)

$$\frac{\partial \overline{v}}{\partial t} = -\overline{u}(\overline{\zeta} + f) - \overline{w}\frac{\partial \overline{v}}{\partial z} + F_\lambda$$



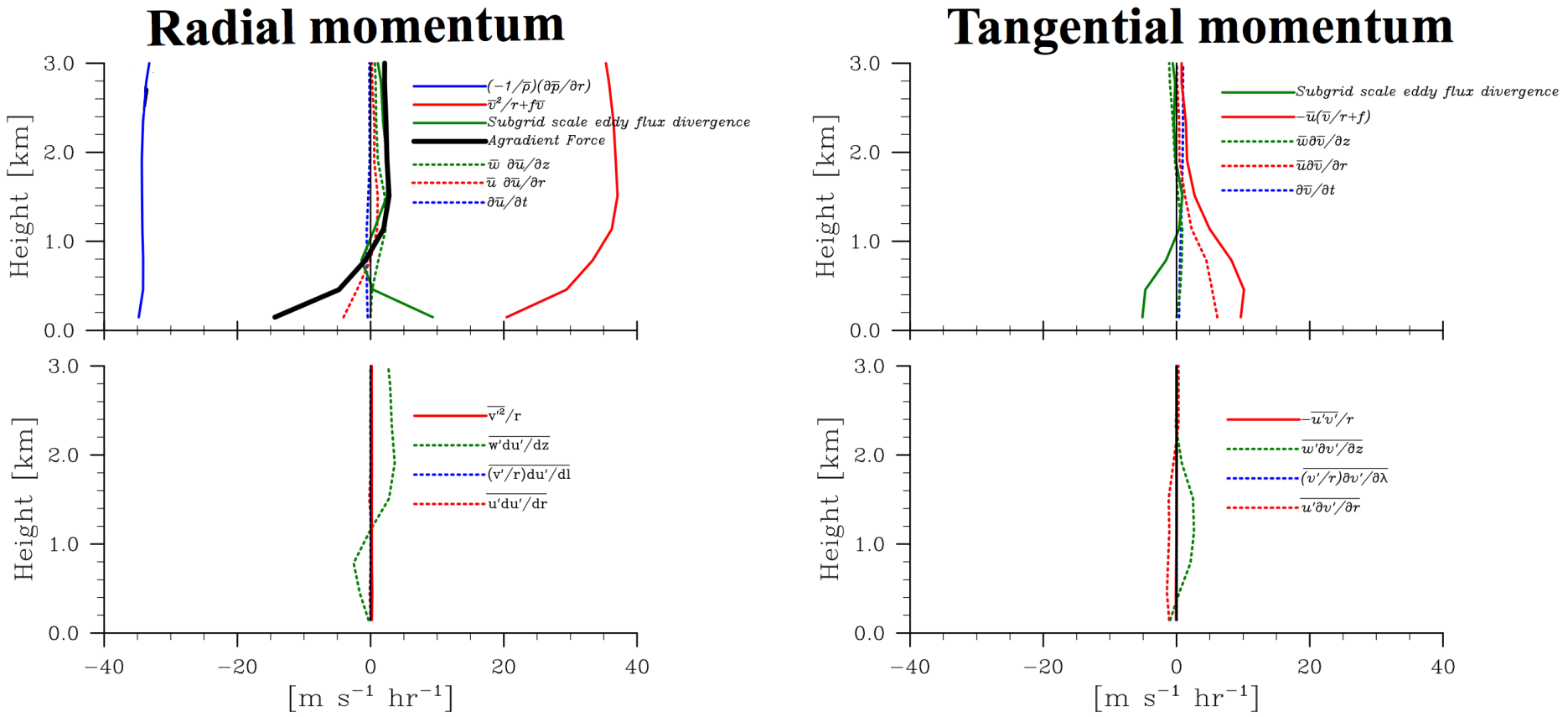
Abarca and Montgomery (2014b)



Abarca and Montgomery (2014b)

Large radii

hr 18, 190-200 km radius

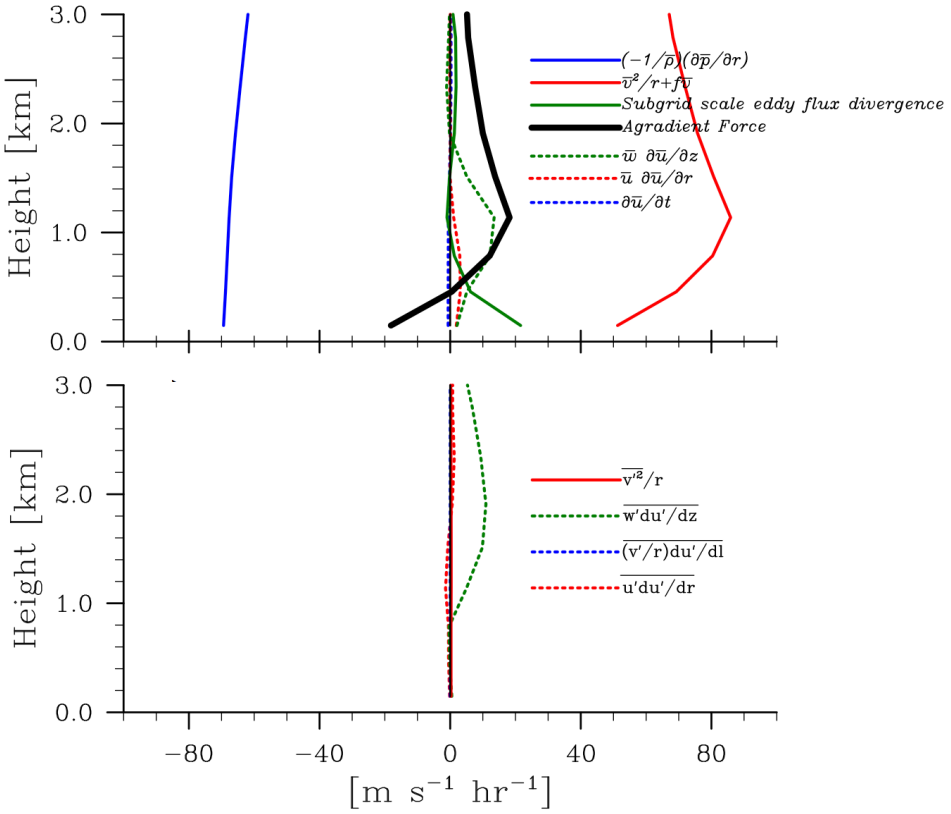


Approximate Ekman-like balance =)

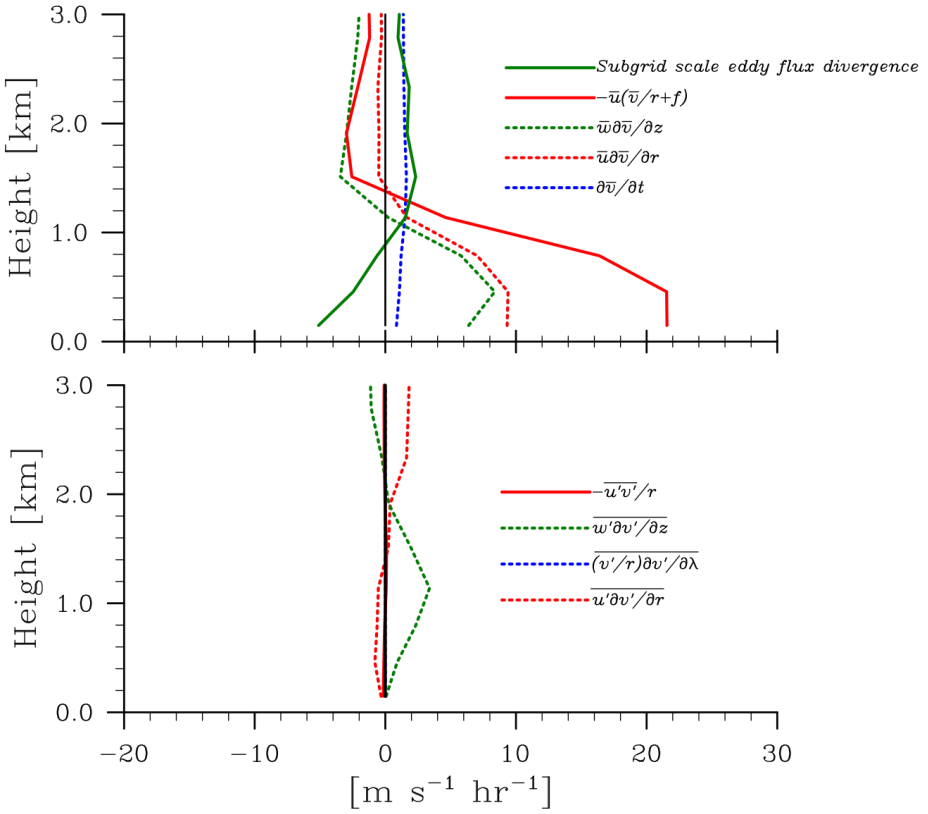
Secondary eyewall formation

hr 18, 110-120 km radius

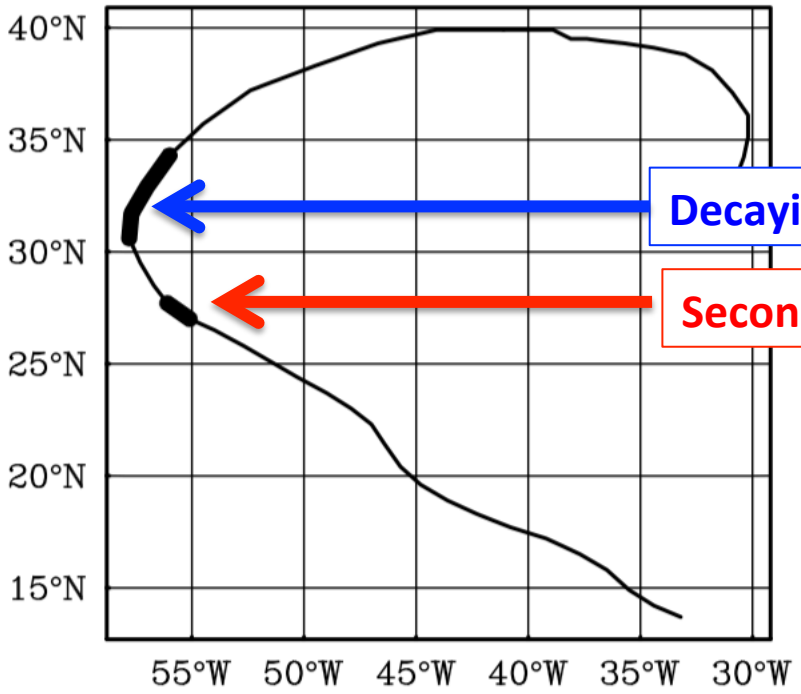
Radial momentum



Tangential momentum

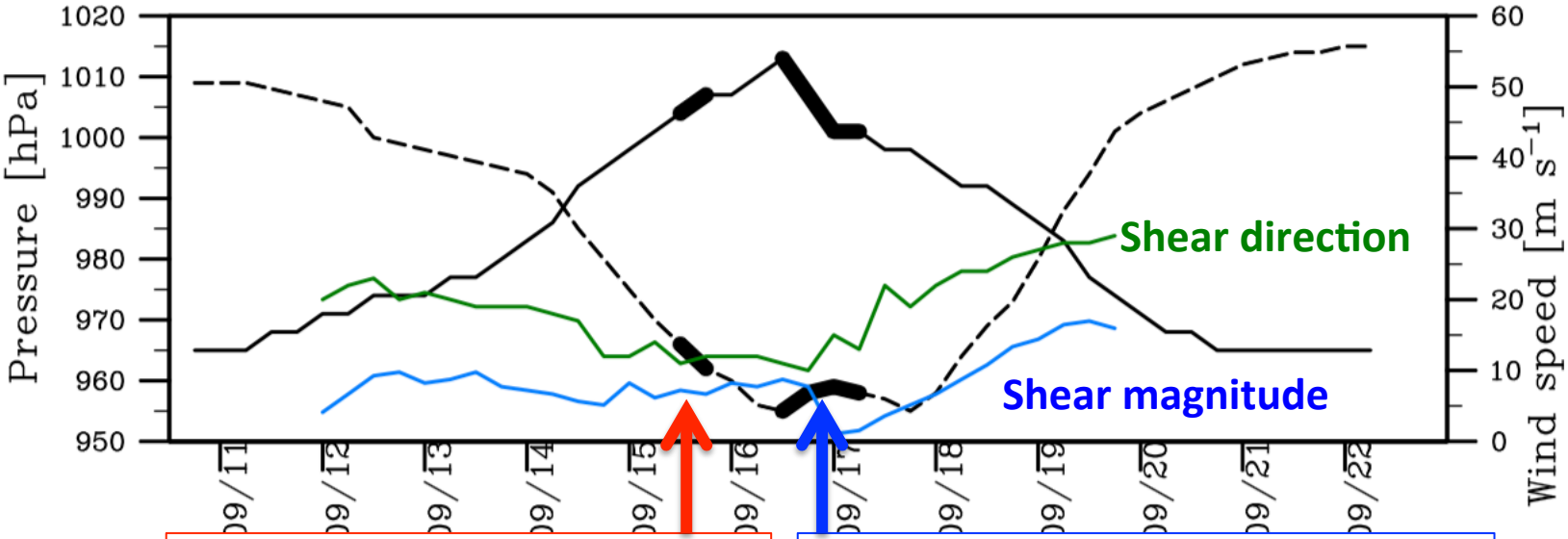


Ekman-like balance is not found =(



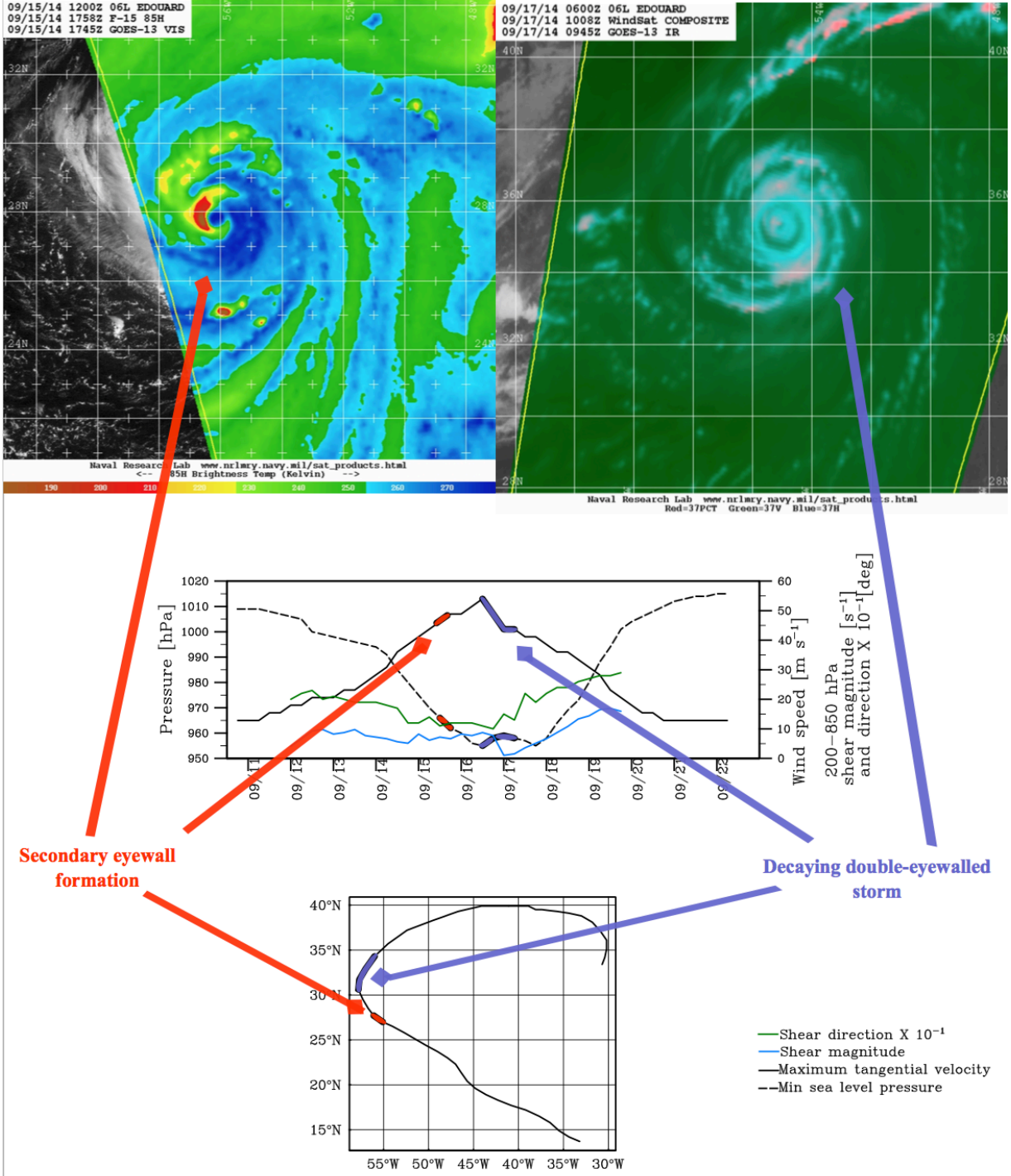
Decaying double-eyewalled storm

Secondary eyewall formation



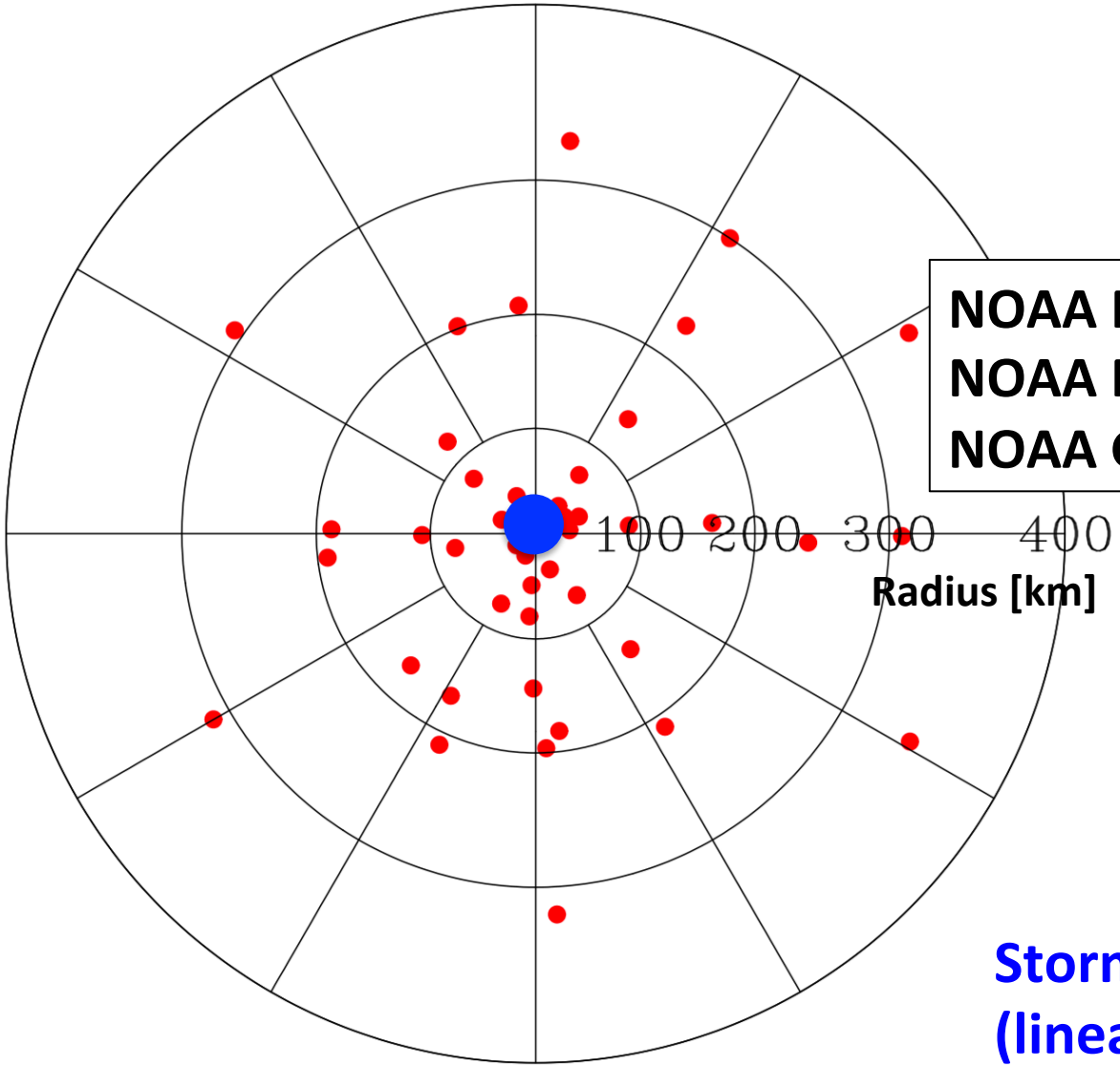
Secondary eyewall formation

Decaying double-eyewalled storm


09/15/14 1200Z 06L EDOUARD
09/15/14 1758Z F-15 85H
09/15/14 1745Z GOES-13 VIS
09/17/14 0600Z 06L EDOUARD
09/17/14 1008Z WindSat COMPOSITE
09/17/14 0945Z GOES-13 IR
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
<-- 85H Brightness Temp (Kelvin) -->
190 200 210 220 230 240 250 260 270
Naval Research Lab www.nrlmry.navy.mil/sat_products.html
Red=37PCT Green=37V Blue=37H
Pressure [hPa]
Wind speed [m s⁻¹]
200–850 hPa shear magnitude [s⁻¹] and direction X 10⁻¹[deg]
09/11
09/12
09/13
09/14
09/15
09/16
09/17
09/18
09/19
09/20
09/21
09/22
Secondary eyewall formation
Decaying double-eyewalled storm
40°N
35°N
30°N
25°N
20°N
15°N
55°W 50°W 45°W 40°W 35°W 30°W
Shear direction X 10⁻¹
Shear magnitude
Maximum tangential velocity
Min sea level pressure

Secondary eyewall formation

9/15 4:13-19:20 UTC



~5 hours

49 dropsondes

NOAA P-3 Orion -5-12 kf, 19 drops
NOAA P-3 Orion– 5-12 kf, 14 drops
NOAA G-IV Jet– 45 kf feet, 16 drops

Storm center from Best tracks (linear interpolation to 10 min)

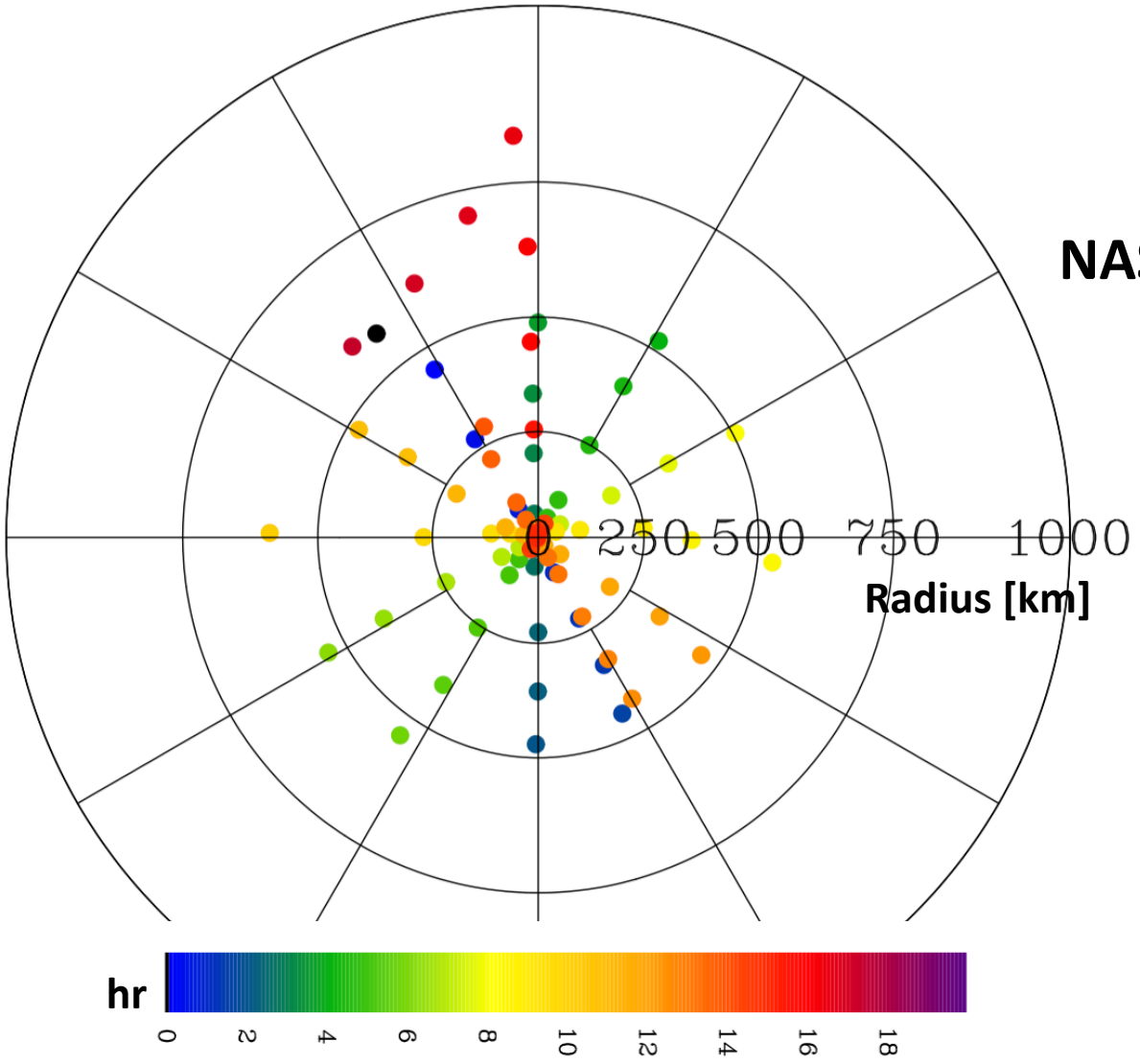
Decaying double-eyewalled storm

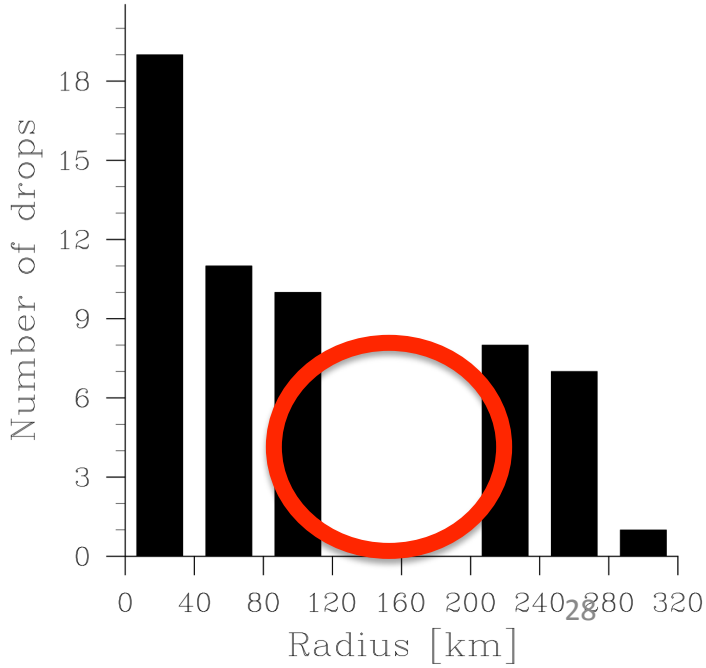
9/16 15:06 UTC – 9/17 08:28 UTC

~18 hours

87 dropsondes

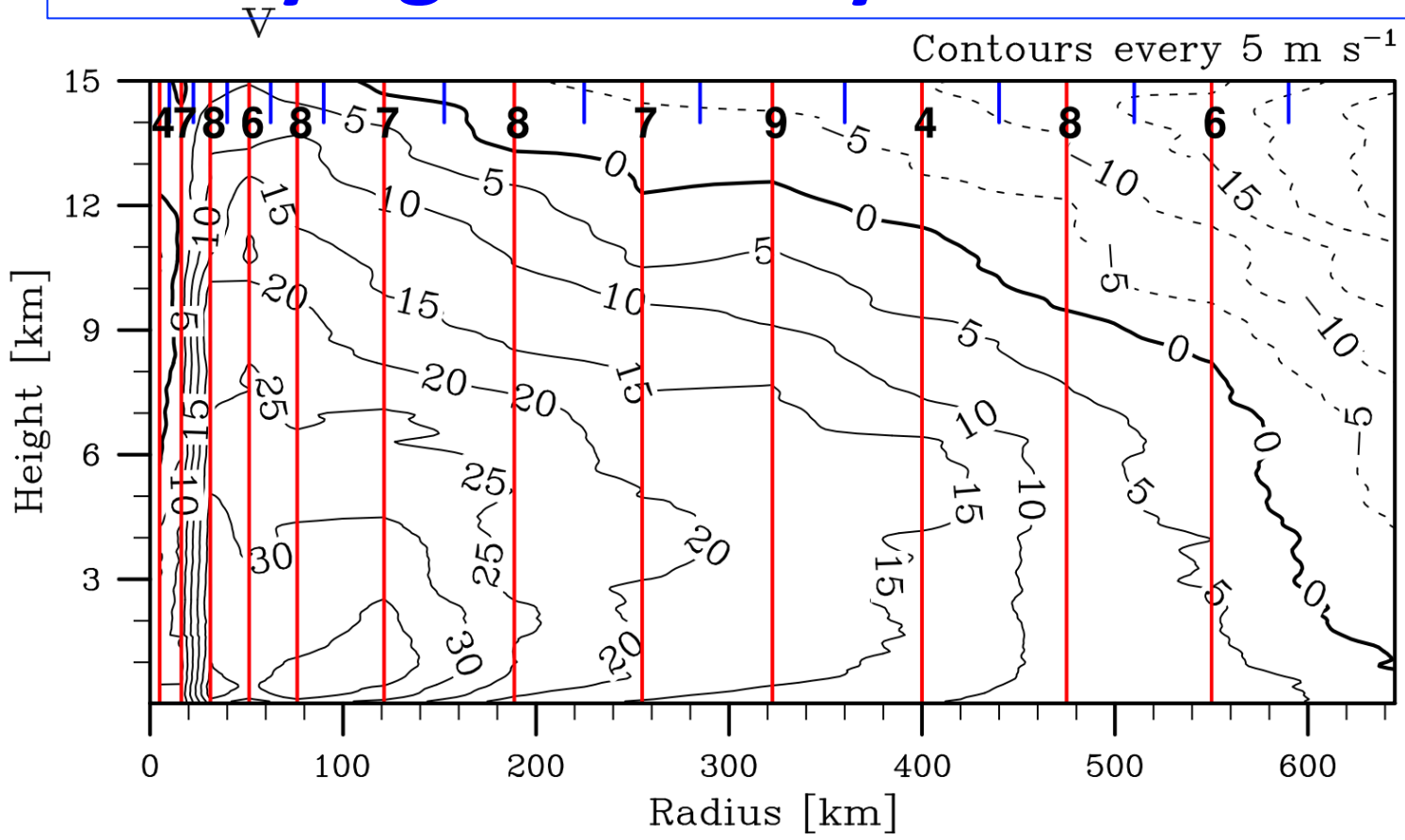
NASA Global Hawk– 55k feet



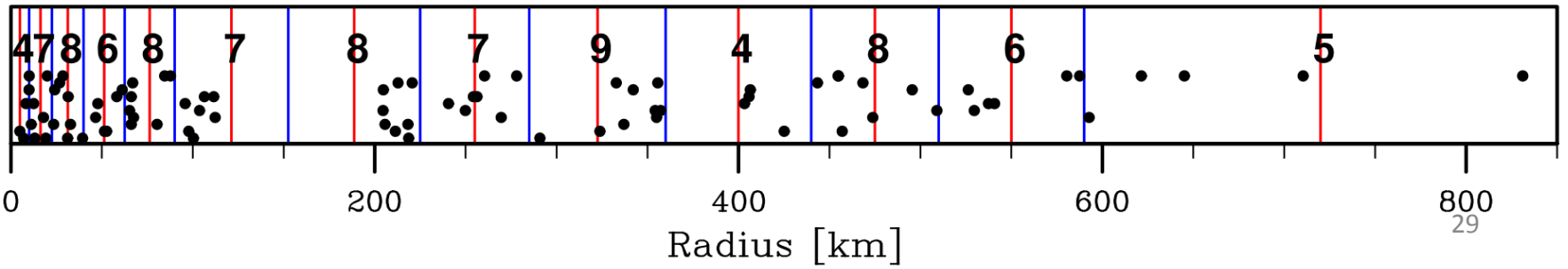


Decaying double-eyewalled storm

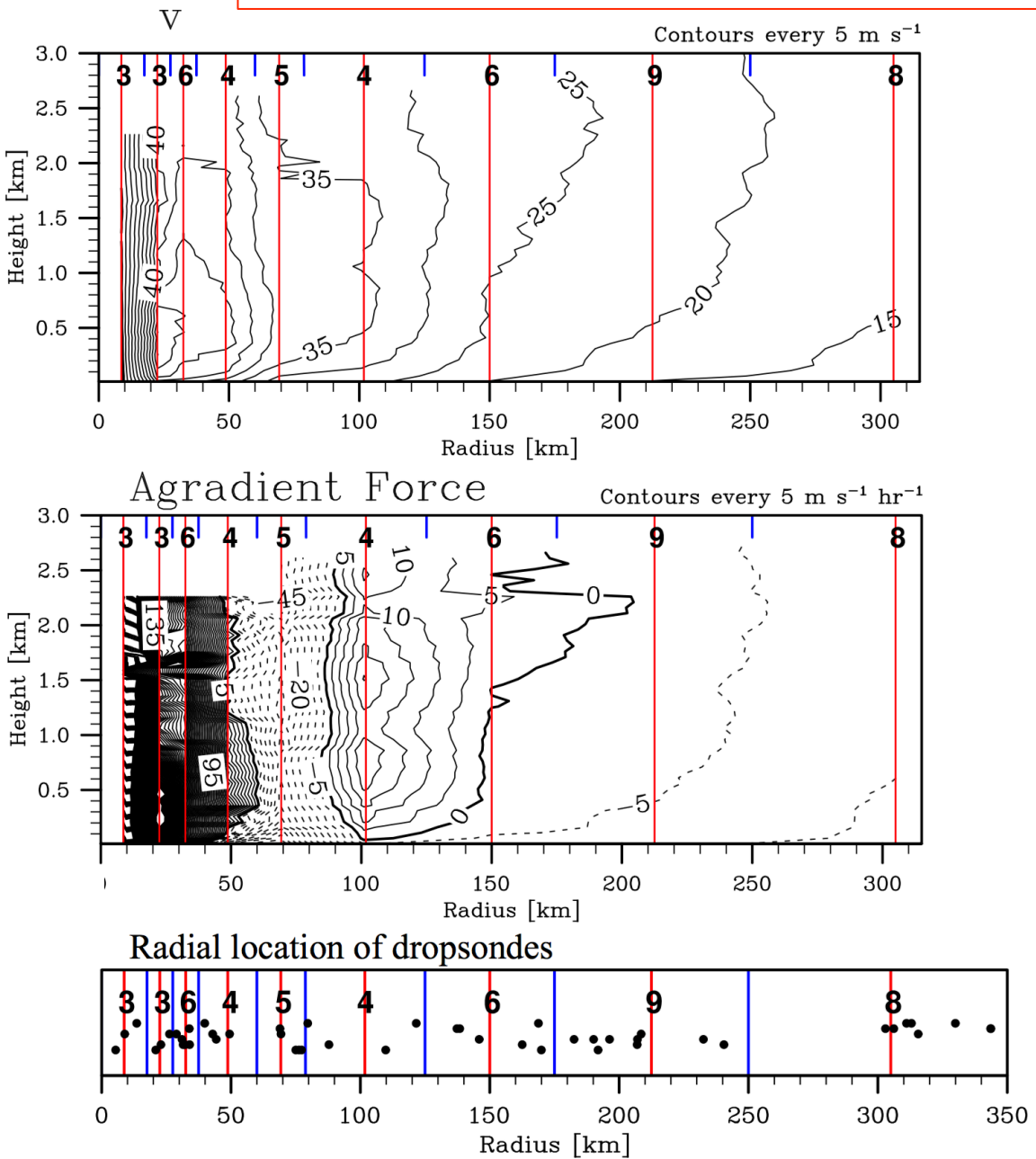
Global Hawk

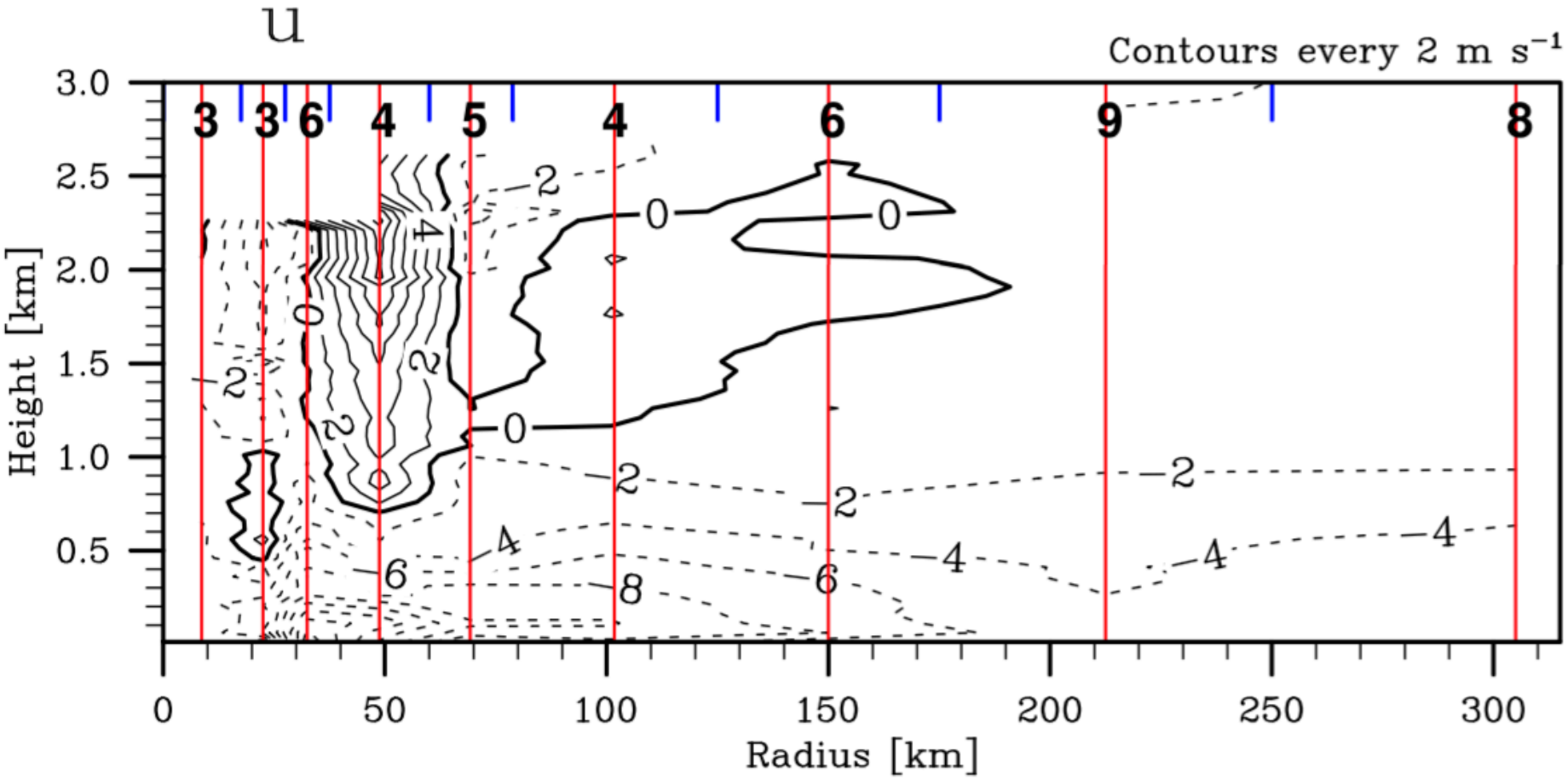


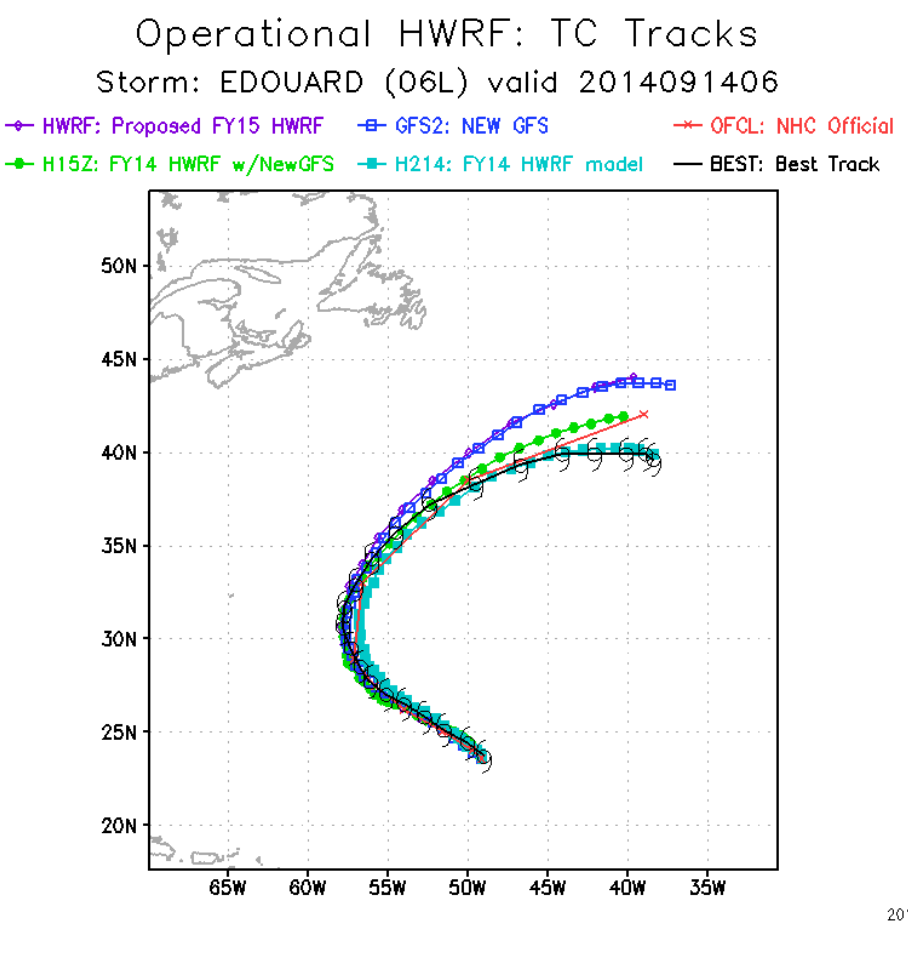
Radial location of dropsondes

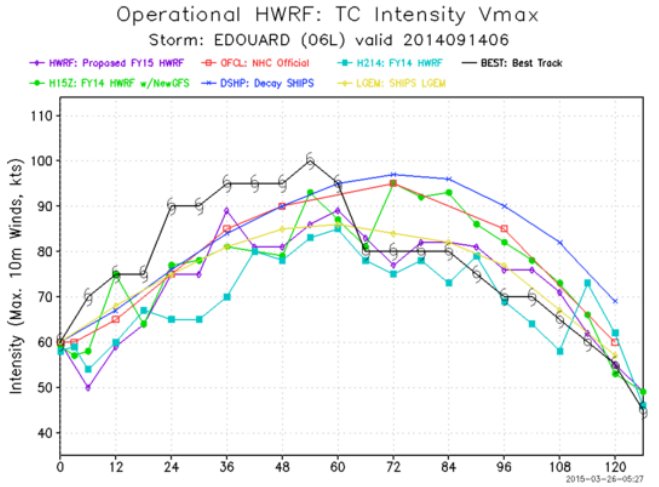


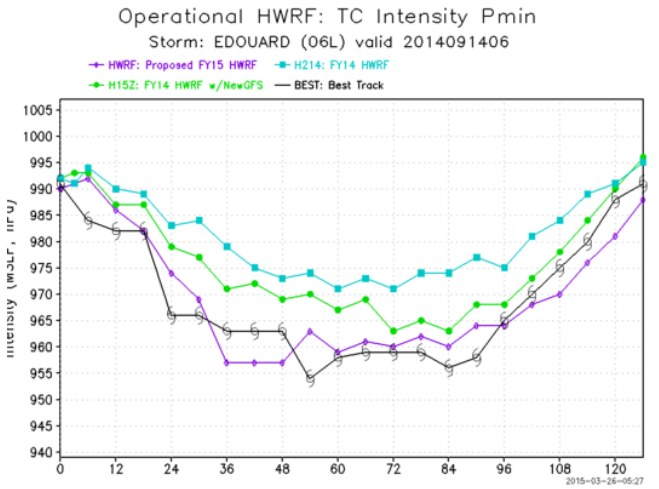
Secondary eyewall formation



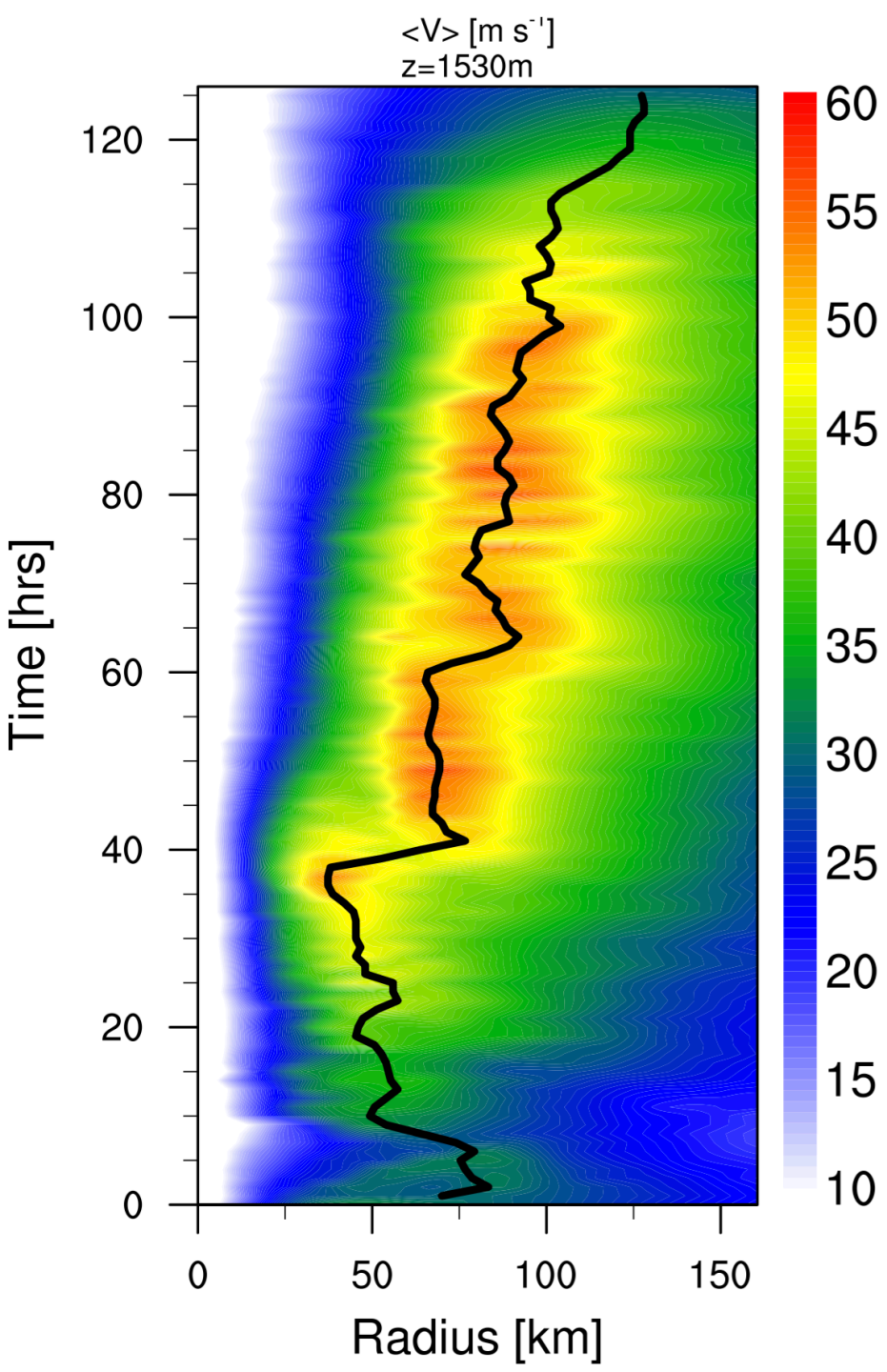

u
Contours every 2 m s^{-1}
3 3 6 4 5 4 6 9 8
Height [km]
Radius [km]
0
50
100
150
200
250
300
0.5
1.0
1.5
2.0
2.5
3.0

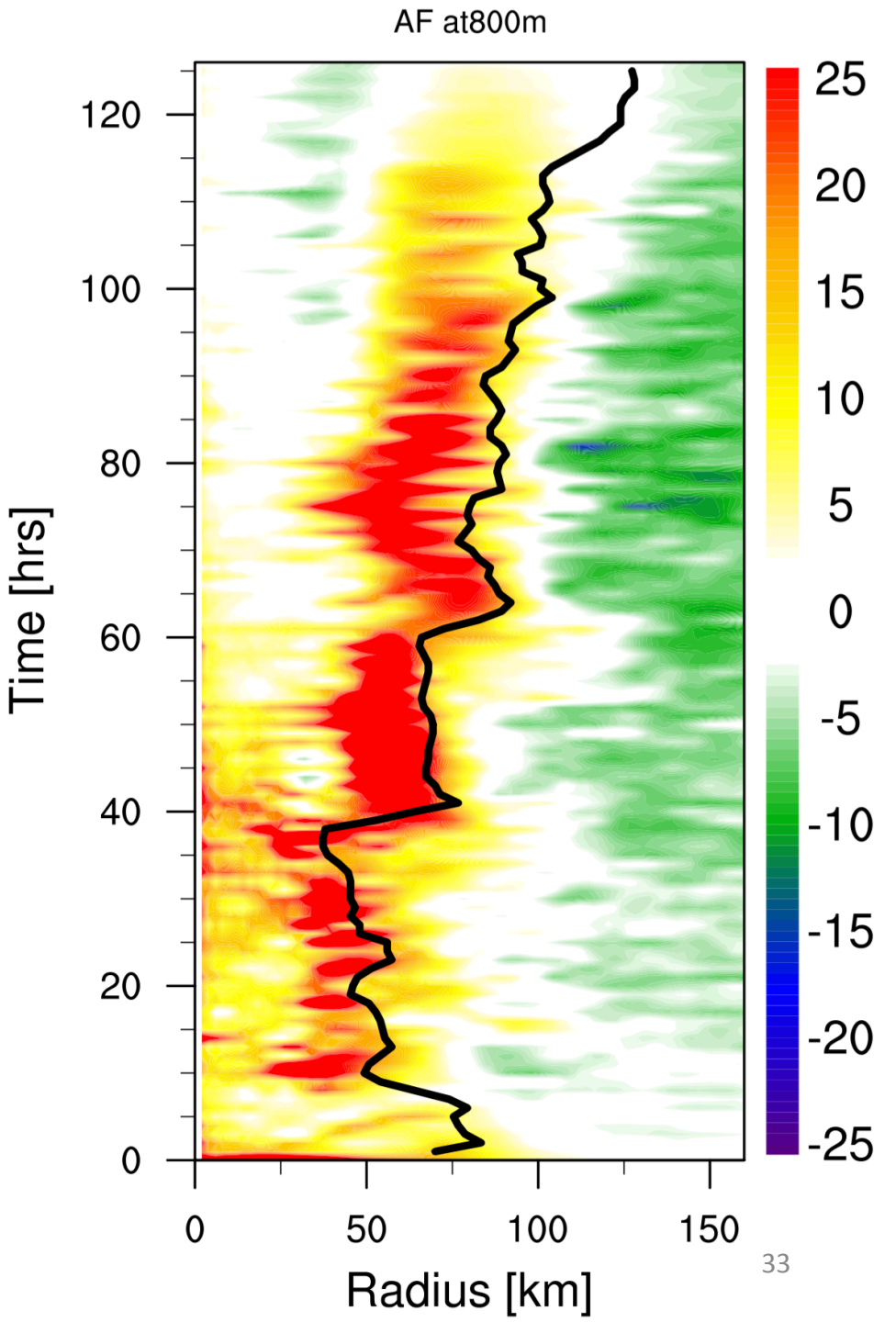


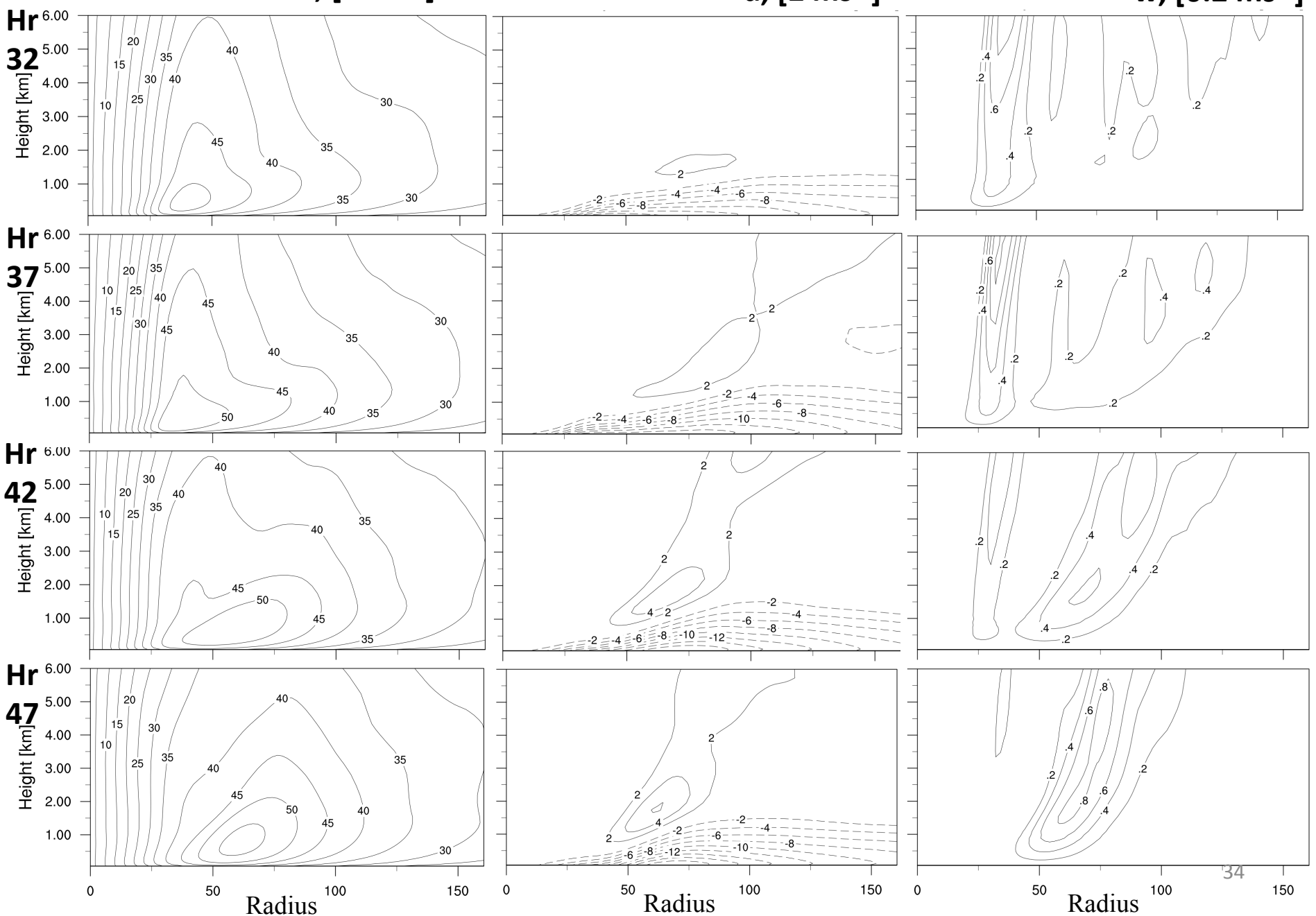


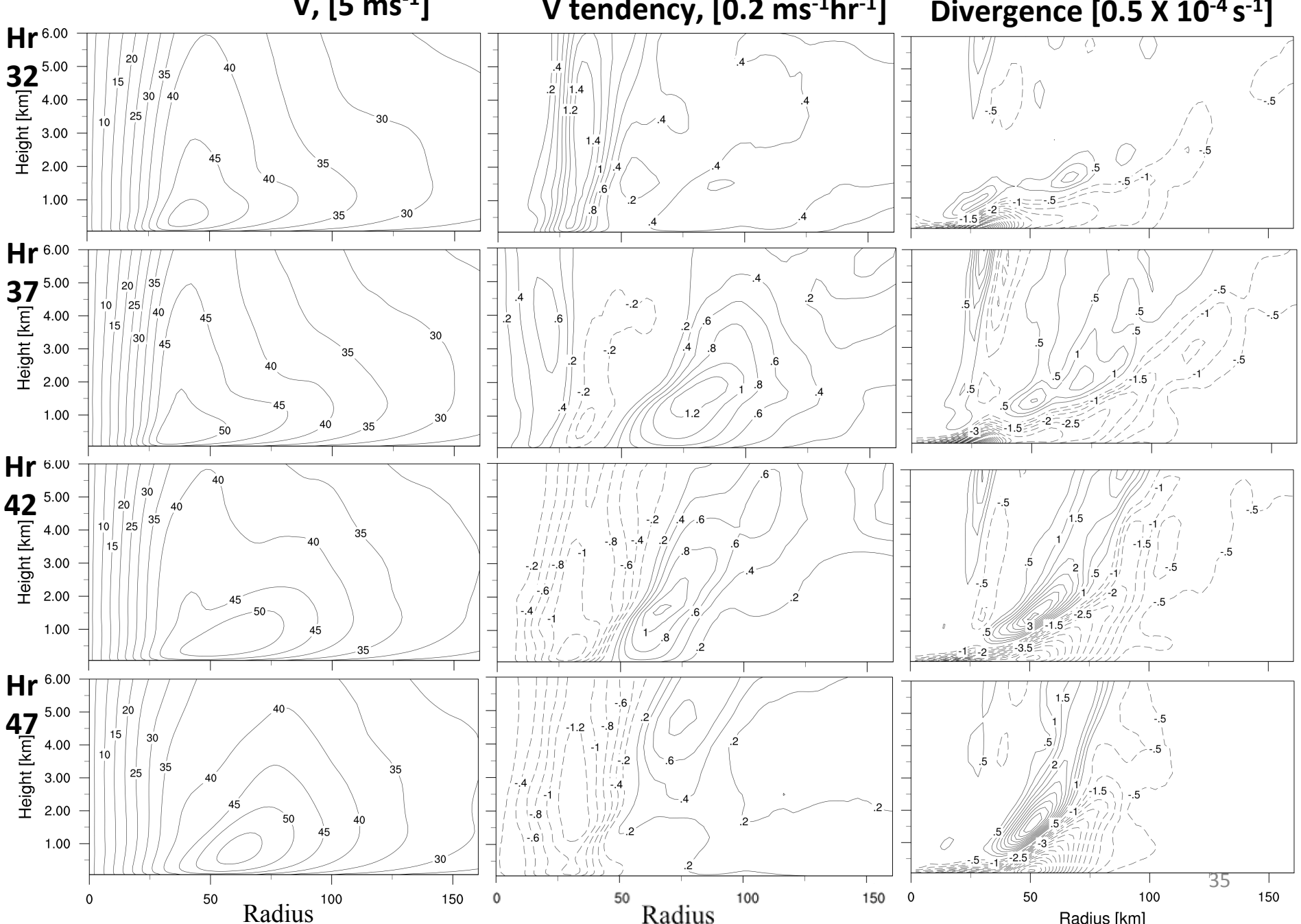


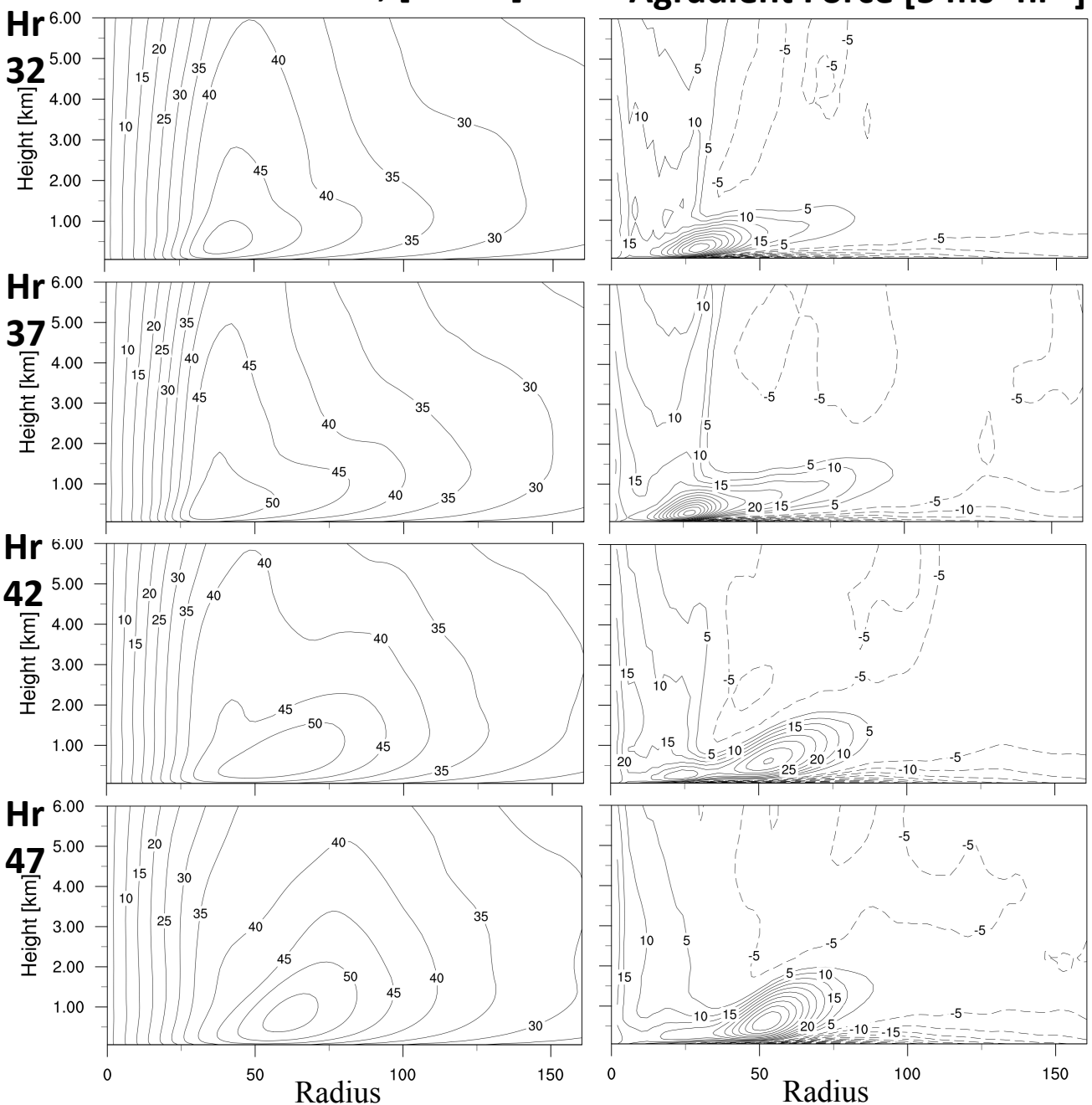
Federico DiCatarina, FSU

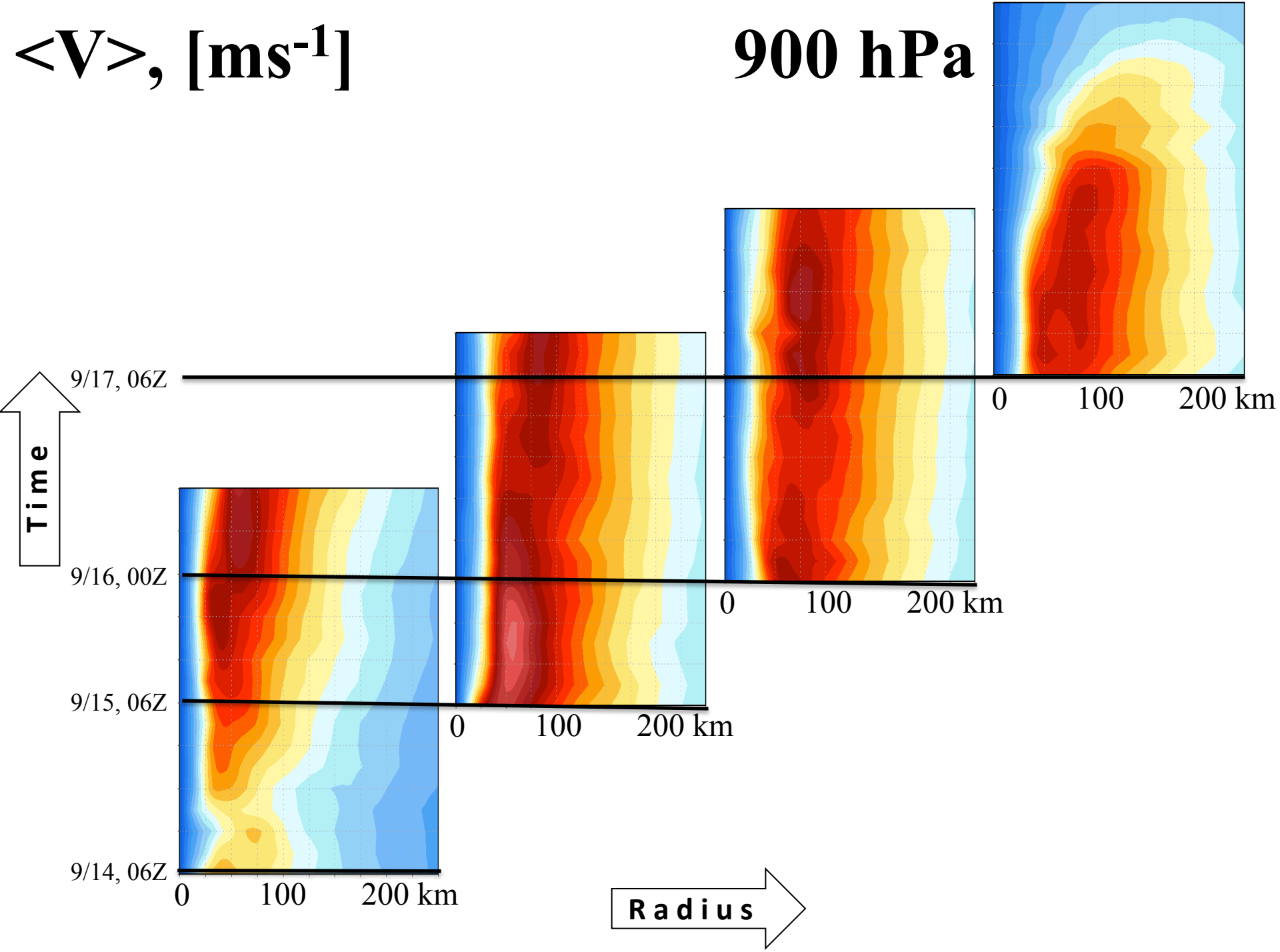

<V> [m s-1]
z=1530m
Time [hrs]
Radius [km]
0
20
40
60
80
100
120
0
50
100
150
60
55
50
45
40
35
30
25
20
15
10


AF at800m
Time [hrs]
Radius [km]
0
20
40
60
80
100
120
0
50
100
150
25
20
15
10
5
0
-5
-10
-15
-20
-25


V, [5 ms-1]
u, [2 ms-1]
w, [0.2 ms-1]
Hr 32
Hr 37
Hr 42
Hr 47
Height [km]
Radius


V, [5 ms-1]
V tendency, [0.2 ms-1hr-1]
Divergence [0.5 X 10-4 s-1]
Hr 32
Hr 37
Hr 42
Hr 47
Height [km]
Radius
Radius
Radius [km]


V, [5 ms-1]
Agradient Force [5 ms-1hr-1]
Hr 32
Hr 37
Hr 42
Hr 47
Height [km]
Radius
Radius


<V>, [ms-1]
900 hPa
9/17, 06Z
9/16, 00Z
9/15, 06Z
9/14, 06Z
Time
0
100
200 km
Radius

Conclusions

- Secondary eyewalls are:
  - Common in nature
  - Rare in mesoscale integrations (not only in HWRF)
- Secondary wind maxima emerges
  - Within the BL
  - After supergradient winds
  - Fundamentally Non-linear region of the storm
- Balanced dynamics alone do not capture SEF or ERC spinup
- Operational HWRF generates SE

Recommendations

- Storm growth
  - Radial expansion of the tangential wind field
- Secondary eyewall formation
  - i.e. not in secondary eyewalls *per se*